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EVALUATION OF FUTURE FUELS IN A HIGH PRESSURE COMMON RAIL SYSTEM – PART 2 2011 FORD 6.7L DIESEL ENGINE

INTERIM REPORT
TFLRF No. 434

by
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Edwin A. Frame
Douglas M. Yost

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Patsy A. Muzzell
Eric R. Sattler
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD0004–Task XII)

January 2013

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EXECUTIVE SUMMARY

A series of fuels were tested in the fuel system for the 2011 Ford 6.7L "Scorpion" Diesel Engine. Included were ULSD, an FT SPK, Jet A, and an SPK/Jet A blend with DCI-4A. Testing occurred at 60 and 80°C over a 400 hour NATO cycle. Fuel viscosity ranged from 0.620 to 1.90 cSt while lubricity wear-scar diameters were from 0.47 to 0.96 mm (ASTM D5001 BOCLE) and 0.47 to 0.83 mm (ASTM D6079 HFFR). At the conclusion of each 400 hour test, components were evaluated for wear and overall system performance with the ULSD test as a baseline for comparison. Results showed that the HPCR fuel system from the Ford 6.7L "Scorpion" had little sensitivity with regards to fuel lubricity and viscosity with even low levels of lubricity improver additive provide adequate system protection.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period May 2011 through January 2013 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank-Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-DP/MS110) served as the TARDEC contracting officer's technical representative. Ms. Patsy Muzzell of TARDEC served as the project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support provided by Dianna Barrera.

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ACRONYMS AND ABBREVIATIONS

%	Percent
˚C	Degrees Celsius
˚F	Degrees Fahrenheit
ASTM	American Society for Testing and Materials
BOCLE	Ball On Cylinder Lubricity Evaluator
CI/LI	Corrosion Inhibitor/Lubricity Improver
cSt	CentiStoke
FT	Fischer-Tropsch
HFRR	High-Frequency Reciprocating Rig
HPCR	High Pressure Common Rail
IDS	Integrated Diagnostic Software
mm	Millimeter
OEM	Original Equipment Manufacturer
PCM	Powertrain Control Module
PCV	Pressure Control Valve
psi	Pounds per square inch
rpm	Revolutions per minute
SAE	Society of Automotive Engineers
SPK	Synthetic-Paraffinic Kerosene
TARDEC	Tank Automotive Research, Development and Engineering Center
ULSD	Ultra Low Sulfur Diesel
VCV	Volume Control Valve
WSD	Wear Scar Diameter

1.0 BACKGROUND AND OBJECTIVE

As industries begin to incorporate renewable fuel sources into global supply, it is in the interest of the U.S. Army to ensure satisfactory ground vehicle operation both now and in the future. With new aviation fuel properties differing from than their petroleum-based counterparts, evaluations are required to validate performance in reciprocating engine fuel injection systems. As environmental regulations drive commercial Original Equipment Manufacturers (OEMs) to reach lower emission levels, the High Pressure Common Rail (HPCR) injection system has become broadly utilized. These systems can operate at pressure up to 30,000 psi to produce multiple highly atomized injection events per cycle. It is critical for the U.S. Army to determine the effect of various future fuels on these systems which are intended for operation on ultra-low sulfur diesel. While many older vehicles in the military fleet do not utilize HPCR style systems, it is likely that they will be used in future commercial engines adapted for military use.

2.0 APPROACH

2.1 TEST FUELS AND TEMPARATURES

The initial test plan included four fuels operated at two temperatures each. These fuels were to be Ultra Low Sulfur Diesel (ULSD), Jet A, a Fischer-Tropsch (FT) process Synthetic Paraffinic Kerosene (SPK) with a minimum treat rate of corrosion inhibitor/lubricity improver (CI/LI) of 9 ppm, and a 50% by volume blend of the Jet A and SPK fuels at a 9 ppm treat rate. The test temperatures were 60°C and 80°C at the inlet to fuel system components, giving an indication as to performance at elevated ambient conditions and high loads. As the project progressed, the matrix was adjusted to ensure useful information was produced from each test. Rather than increasing the temperature of the blended fuel for the second test, additional DCI-4A was added to determine wear sensitivity. The final evaluation of the system was a combination of two fuels, neat Jet A and SPK, to isolate the cause of an issue seen in the pump shaft bushing, as well as an opportunity to test the limits of the injectors. The final test fuels matrix is shown in Table 1.

Table 1. Project Test Fuels

Fuel	Test Temp. (°C)	Viscosity @ Test Temp. (cSt)	Lubricity (Fresh), WSD (mm)	
			ASTM D5001	ASTM D6079
Ultra Low Sulfur Diesel	60	1.90	0.47	0.48
Jet A	60	0.91	0.61	0.74
Jet A	80	0.74	0.61	0.74
Jet A (Clay Treated, Test #8)	60	0.91	0.81	N/A
SPK (9 ppm CI/LI)	60	0.75	0.82	0.83
SPK (9 ppm CI/LI)	80	0.62	0.82	0.83
SPK (Clay Treated, Test#8)	60	0.75	0.96	N/A
50% Jet A, 50% SPK (9 ppm CI/LI)	60	0.83	0.66	0.71
50% Jet A, 50% SPK (22.5 ppm CI/LI)	60	0.83	0.56	0.76

Fuel was sampled at the end of each 100 hours and measured for lubricity using ASTM D6079 [1] and D5001 [2]. Results of this for the first seven evaluations are shown in Figure 1 and Figure 2.

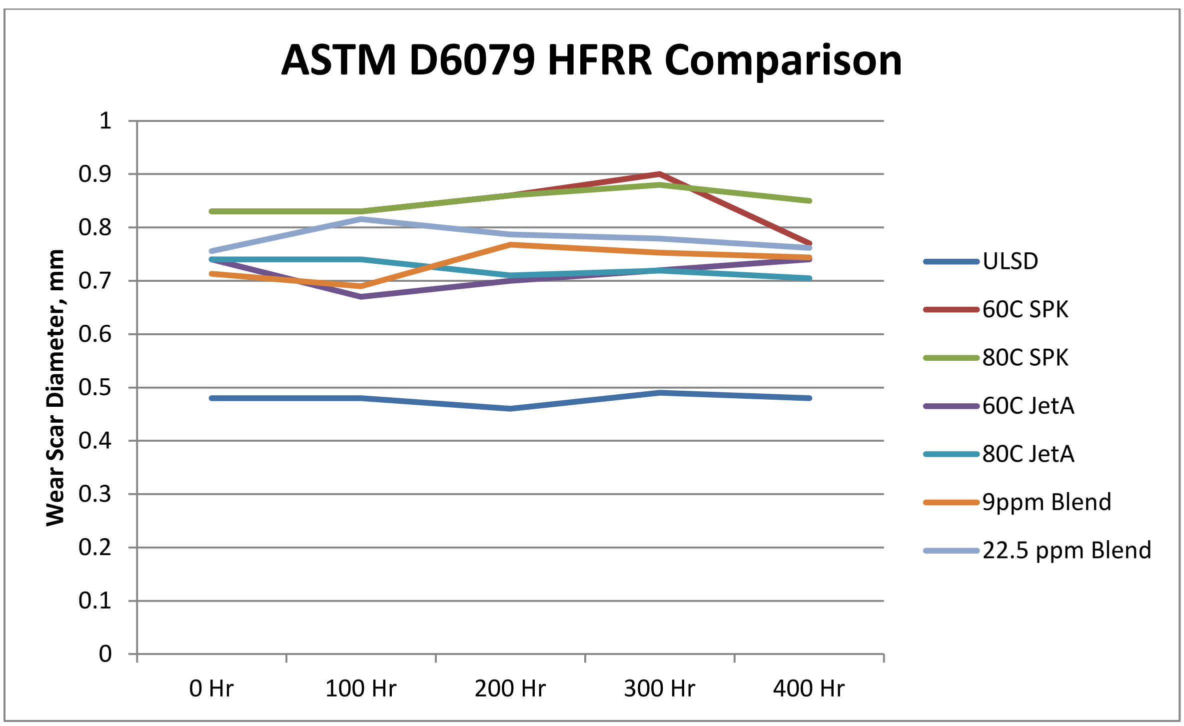


Figure 1. ASTM D6079 HFRR Comparison

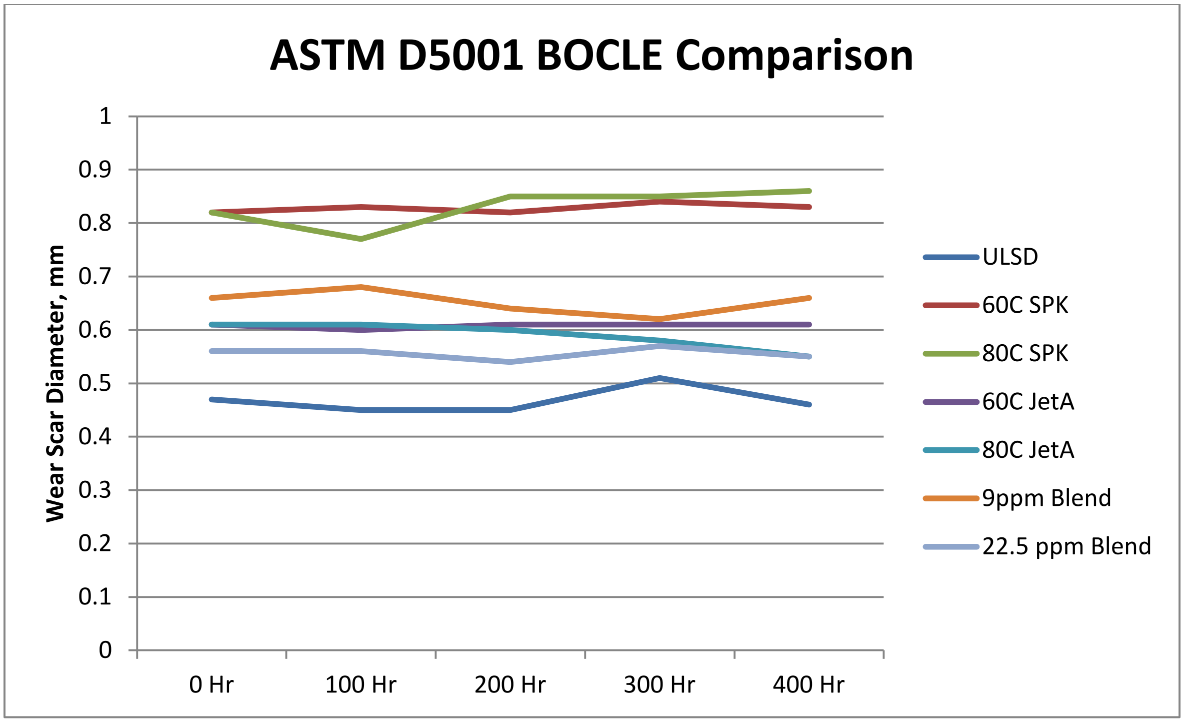


Figure 2. ASTM D5001 BOCLE Comparison

2.2 TEST CYCLE

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400 hour test consisting of repeated 10 hour cycles. Each cycle has 10 operating modes with controlled speed and load. Since there is no torque feedback available when using the fuel system alone, “load” was determined based upon the accelerator pedal input supplied to the Powertrain Control Module (PCM). This value was read over the Ford Motor Company Integrated Diagnostic Software (IDS) tool. The pump was driven at the speed which it would turn if run on an engine, same as that of the crankshaft. The operating modes for the cycle are shown in Table 2.

Table 2. NATO Cycle for Ford 6.7L Pump Stand

Step	Pump Speed, rpm	Throttle, %	Duration, hours
1	600	0	0.5
2	2800	100	2
3	2940	0	0.5
4	2100	100	1
5*	600 to 2800	0 to 100	2
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2
10	1680	50	0.5

*Step 5 cycles between idle and rated conditions

2.3 TEST STAND AND FUEL SYSTEM

2.3.1 Fuel Pump

The HPCR system consists of a low pressure electric lift pump and high pressure supply pump, the Bosch CP4.2. The lift pump is integral to the fuel/water separator and runs on vehicle power. The high pressure pump is driven at a 1:1 speed ratio with the crankshaft. Pistons within the pump are oriented in a “V” configuration and driven off of common camshaft lobes. Examples of the pump housing can be seen in Figure 3 and Figure 4.

Figure 3. Pump Housing, Front

Figure 4. Pump Housing, Rear

A bushing pressed into the rear of the pump housing provides support for the pump camshaft. This shaft has two lobes which drive the high pressure plungers. An image of the shaft can be seen in Figure 5 along with the front cover and bushing in Figure 6.

Figure 5. High Pressure Pump Camshaft

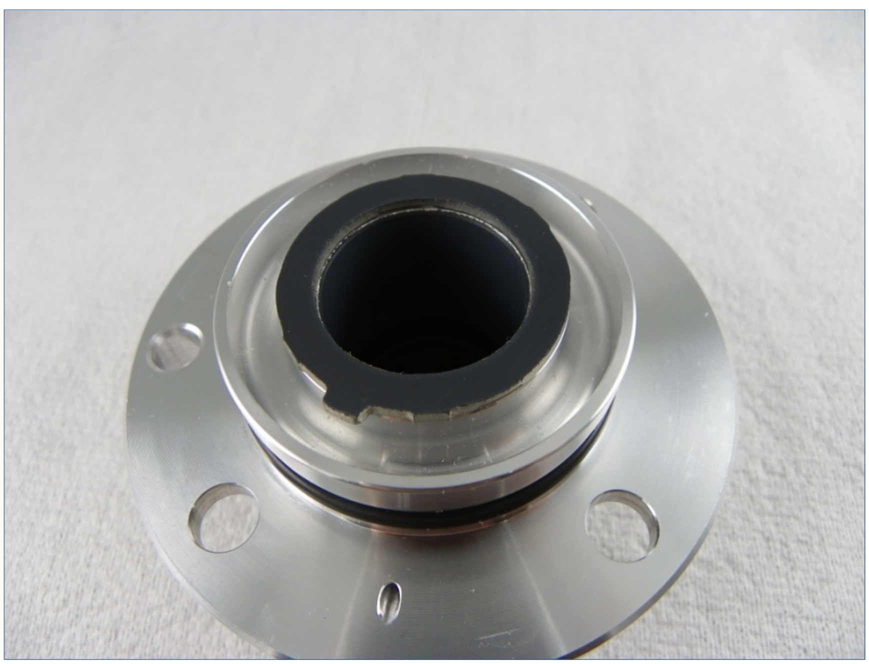


Figure 6. Pump Front Cover and Bushing

The small hole visible in the front cover allows for fuel to flow around the camshaft in the bushing for lubrication and pass back into the return fuel path within the pump housing.

The direction of fuel flow into and out of the pump housing is indicated by the arrows on the back of the pump body in Figure 4. Once in the pump housing, fuel was directed either to the return line or high pressure plunger supply by the Volume Control Valve (VCV). This valve can be seen in Figure 7.

Figure 7. Volume Control Valve

From this control valve, fuel is supplied to each of the high pressure plungers through inlet check valves. These valves allow fuel to pass into the plunger bore on the down stroke, but close under the pressure developed in the compression stroke. These valves open under the fuel pressure supplied from the system lift pump, typically between 50 and 67 psi. The check valve location is shown in Figure 8, while Figure 9 shows the component removed from the pump head.

Figure 8. Check Valve in Pump Head

Figure 9. Inlet Check Valve

The plungers are guided by a roller-follower from the cam lobes. The follower is shown in Figure 10 while the plunger is shown in Figure 11. By using a roller-follower guided within the pump bore, the plunger experiences limited forces other than axial compression.

Figure 10. Camshaft Follower

Figure 11. High Pressure Plunger

As the plunger is driven up by the cam lobes, fuel is pressurized in the two pump heads through a series of check valves and sent on to the fuel supply rail. At the rail, an electronically controlled pressure relief valve enables the PCM to make rapid fine-tuning pressure adjustments or to quickly reduce rail pressure during deceleration events.

2.3.2 Fuel Injectors

Injectors are piezoelectric style controlled by the system PCM. Fuel is supplied by the common rails and returned through a low-pressure flexible line to the inlet of the final fuel filter. An injector is shown in Figure 12 disassembled.

Figure 12. Injector Disassembled

At the top of the injector is the piezoelectric crystal stack, which expands when energized, shown in Figure 13.

Figure 13. Piezoelectric Stack

When energized, the end of the stack presses on the top (right end) of the hydraulic coupling shown in Figure 14, forcing it into the coupling chamber.

Figure 14. Hydraulic Coupling

Since the upper piston in the coupler has a larger diameter than the lower, there is an increased distance of travel in the lower portion of the coupling when the piezoelectric stack is energized. The point of the lower coupling piston opens the injector control valve (Figure 15) which is otherwise seated in the bottom of the Control Valve Plate (top: Figure 16, and bottom: Figure 17).

Figure 15. Injector Control Valve

Figure 16. Control Valve Plate, Top

Figure 17. Control Valve Plate, Bottom

When the control valve is unseated it allows fuel to flow past. This flow comes through the intermediate plate (Figure 18) and reduces the pressure on the top of the injector needle allowing lift.

Figure 18. Intermediate Plate

Below the intermediate plate is the injector needle and holder. The needle, along with spacers and spring, is shown in Figure 19.

Figure 19. Injector Needle

Fuel is supplied to the needle from the top of the injector, through both plates, and around the bore in which the needle is located. The piezoelectric stack being energized changes the balance of pressure on the needle, causing it to lift and fuel to be injected into the cylinder.

2.3.3 Stand Configuration

The system was installed on an existing test bench for the evaluation of HPCR systems. All temperature monitoring, control, and data acquisition was conducted by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a vehicle powertrain control module (PCM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The evaluation was conducted using a 55-gallon drum as remote fuel source for the stand. A diaphragm air pump supplied the fuel to a small day tank located on the stand. Fuel was drawn by the vehicle lift pump from the day tank through heating equipment and 10μm primary filter and water separator to prime the main fuel pump. A final high-efficiency 4μm filter was located between the vehicle lift pump and high pressure pump. A stainless steel manifold was constructed to hold the injectors and fuel rails the same configuration as an engine install. This can be seen in Figure 20.

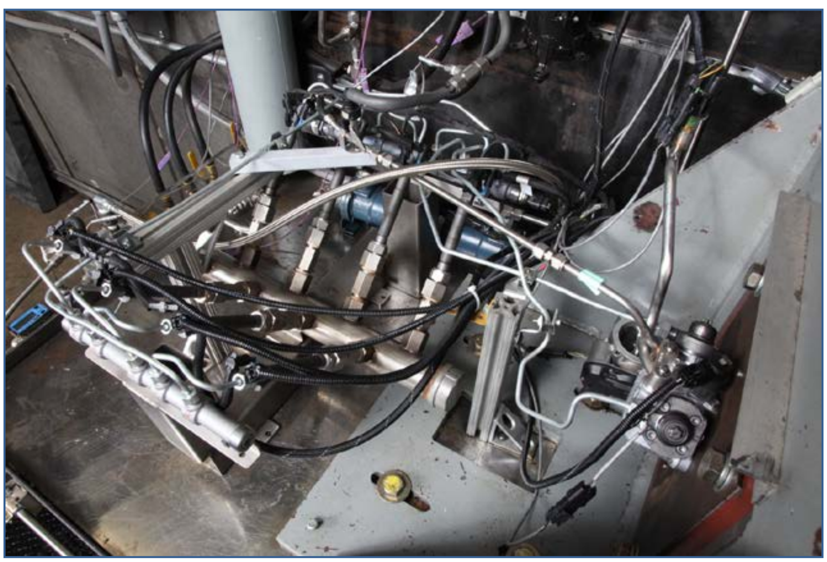


Figure 20. Injector Collection Manifold

Injected fuel, at relatively high temperature, was collected in this manifold and passed through a heat exchanger with the fuel flowing from the day-tank to the circulation heater. This allowed the day tank to maintain a lower temperature and reduced the electrical load of the heater. A layout of fuel flow through the stand is shown in Figure 21.

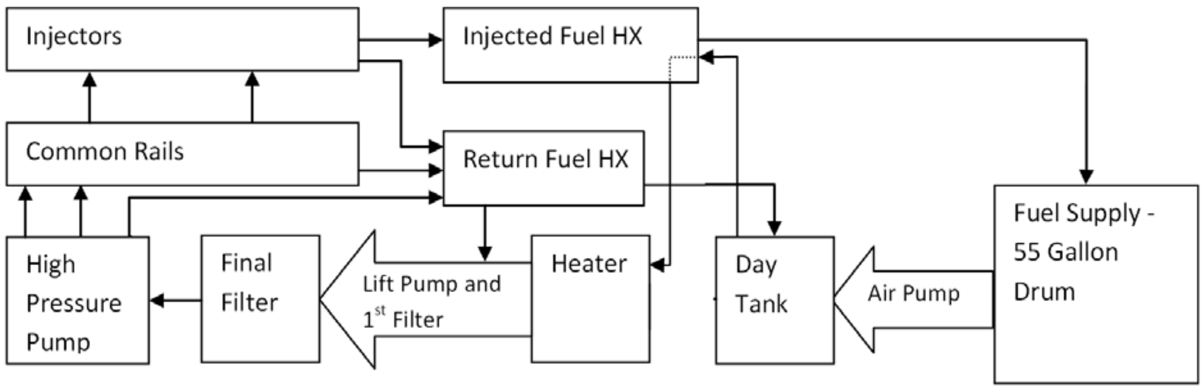


Figure 21. Fuel Flow Layout

The physical stand is shown, fully installed with instrumentation, in Figure 22.

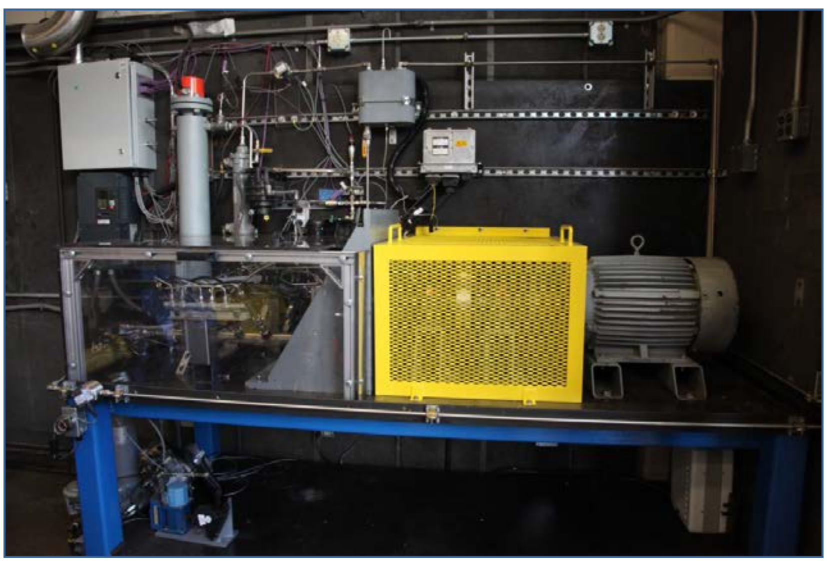


Figure 22. Stand Installation

2.3.4 Test Components

Each test utilized a new set of eight injectors, both fuel filters, and high pressure pump. Between fuels, lines were drained, rinsed with iso-octane as needed, and the entire system flushed with approximately 20 gallons of the next fuel to thoroughly rinse all components. Fuel was sourced from, and returned to, a 55-gallon drum located outside of the test cell. Fuel samples were taken after every 100 hours of test time to monitor changes in fuel lubricity.

3.0 EVALUATION RESULTS

3.1 SYSTEM PERFORMANCE AND OPERATION (TESTS #1-7)

Data points from the two hour "peak power" step, Mode 2, were evaluated as an indicator of overall system health and performance. The figures that follow show various measured parameters over the 40 cycles of each test in comparison. Data points were logged at a rate of once per 60 seconds and the first two data points from each cycle were eliminated to allow for stabilization before taking the mean value for the remaining 118 minutes.

3.1.1 Rail Pressure

The fuel rail pressure, Figure 23, was controlled by the PCM based upon the system speed and throttle input. A high pressure transducer provided a voltage signal to both the PCM and data acquisition software. Rail pressure remained within the range of what would be considered noise of the sensor due to its resolution (1mV = 120 psi). No performance issues can be derived from the system rail pressure for any of the seven evaluations.

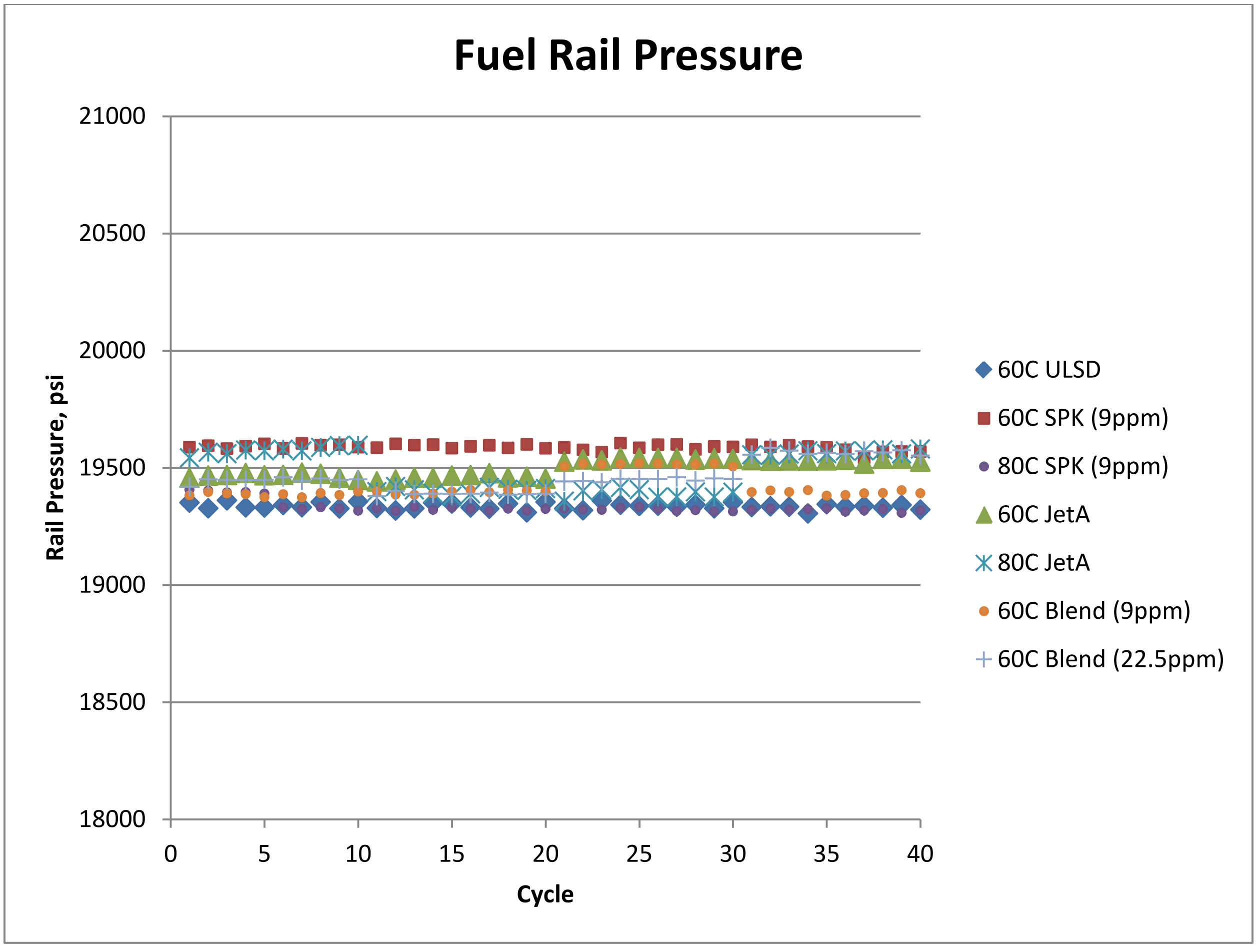


Figure 23. Fuel Rail Pressure

3.1.2 Lift Pump Pressure

The lift pump outlet pressure, Figure 24, was measured prior to the final filter element. A decrease in outlet pressure could have been an indication of lift pump degradation, wear causing a decrease in flow restriction, or additional return fuel flow from a component. It can be seen that at many of the steps following fuel drum changes experienced an increased pressure, followed by a decreased pressure in the next cycle. This may be due to heating and expansion of pump clearances as the test runs. Since the stand is given time to cool down at each 100-hour interval, it would be expected that the metal in the pump body was still heating up after the thirty minute idle condition step which starts the NATO cycle. For the ULSD and both Jet A tests, the pump outlet pressure was largely unchanged from beginning to the end of the test. Both blended fuels, and to a lesser extent the lower temperature SPK test, experienced a few psi loss of lift pump pressure over the course of the test likely related to degradation of the front pump bushing. The high temperature SPK test had a substantial decrease in pump outlet pressure, much larger than that seen with other fuels. This is, again, expected to be related to the pump shaft bushing degradation since the effect did not carry over to other tests once new test hardware was installed on the stand. The drop in pressure for the lower temperature Jet A test between cycles 5 and 10 was due to an issue with the temperature controller overheating the fuel. Upon correction, the pressure returned to a stable range.

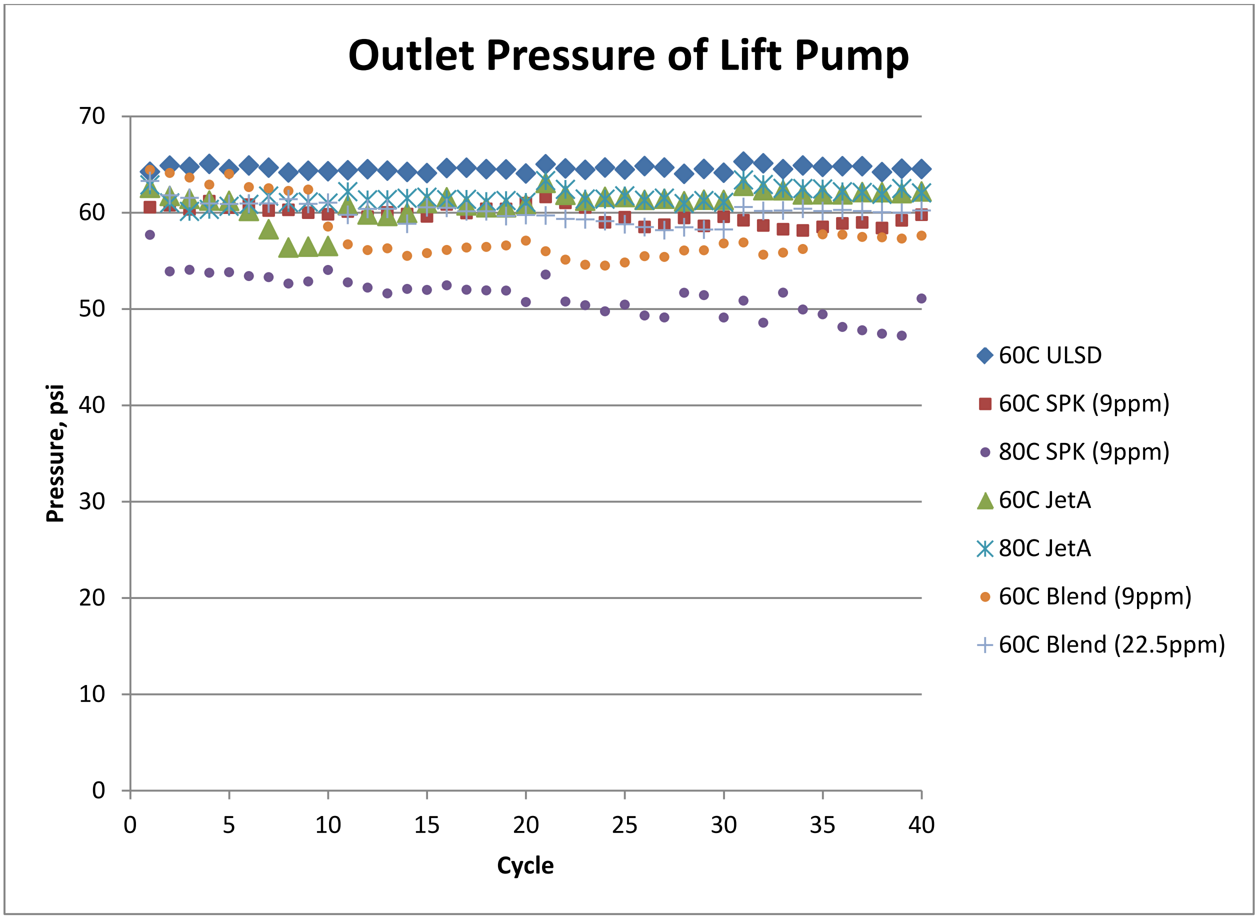


Figure 24. Outlet Pressure of Lift Pump

3.1.3 Injected Fuel Flow Rate

Injected fuel was collected from the eight injectors in a common manifold before being cooled, flow rate measured, and returned to the fuel drum. Flow rates can be seen in Figure 25. It was noted that the ULSD, with a test viscosity of 1.9 cSt, had a lower flow rate than any other fuel. This type of difference in flow rate had been noted in other HPCR applications and was expected [4].

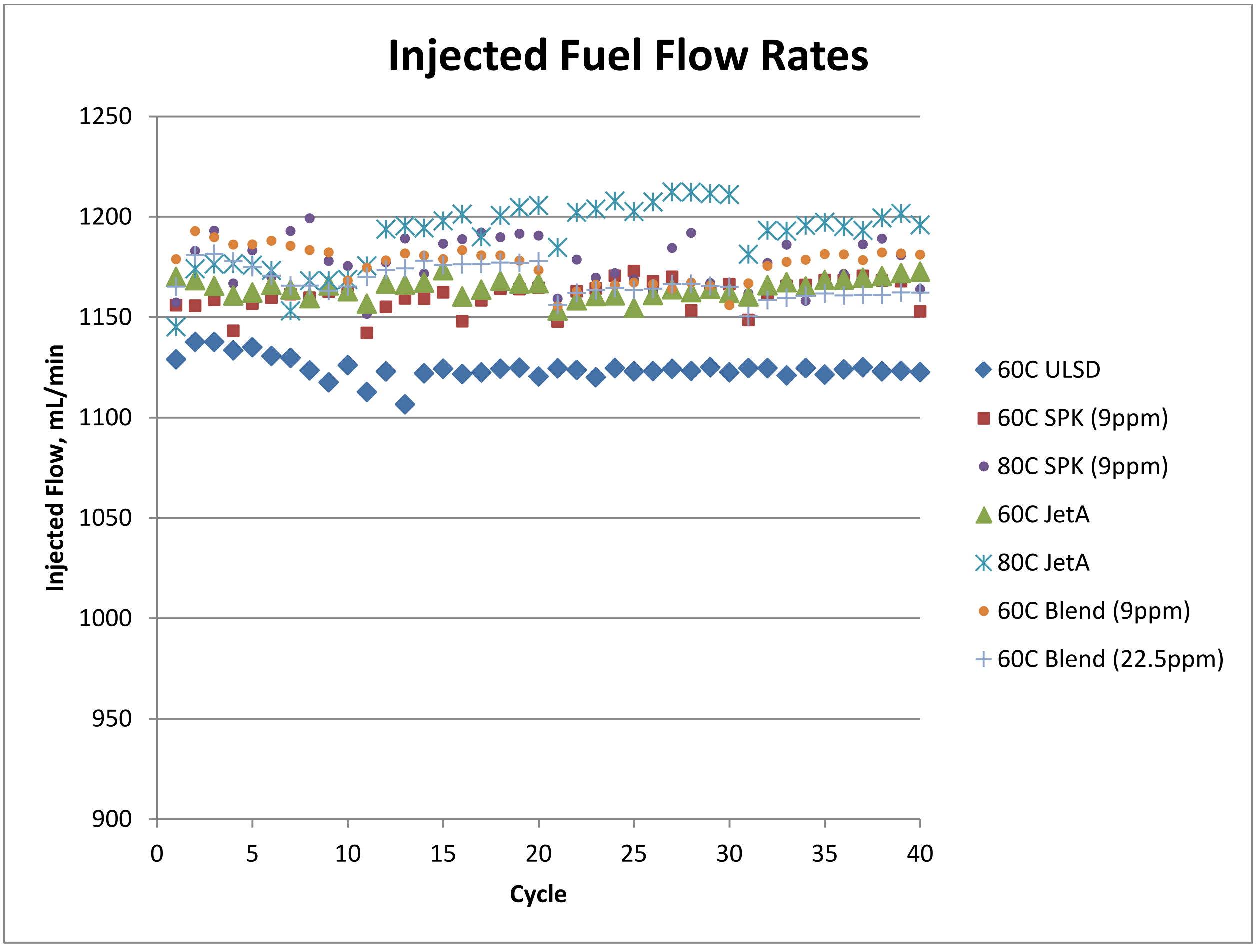


Figure 25. Injected Fuel Flow Rates

3.1.4 Bypass and Return Fuel Flow Rate

The bypass and return fuel flow is a combination of fuel that is diverted back from the pump before being brought up to rail pressure and what is released through the high pressure relief valve on the fuel rail. Injector returns are not measured in this since they are routed back into the high pressure pump rather than returned to a tank. The combined return flow rate for each test is shown in Figure 26.

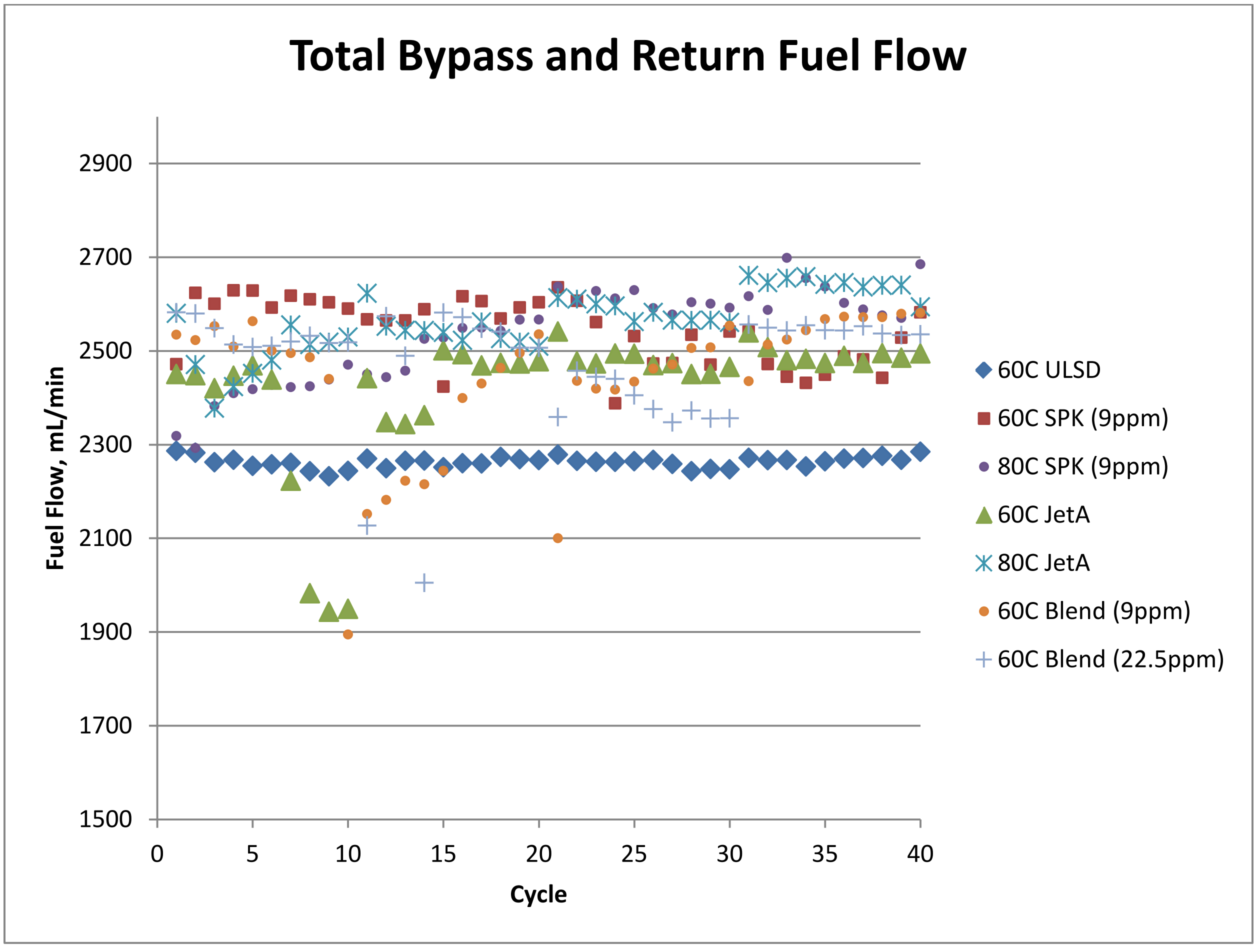


Figure 26. Bypass and Return Flow

Again, the higher viscosity ULSD fuel generally experienced a lower flow rate than the others. The lower temperature Jet A test had a reduced flow rate while experiencing temperature control issues (as noted in Figure 24) while the two Blended fuel tests experienced a variation in flow rate likely associated with the front bushing of the pump. The increase in flow for the high temperature SPK (9 ppm) test is consistent with the decrease seen in lift pump outlet pressure. Some of the variation in flow from cycle to cycle among the tests may be attributed to ambient conditions within the test cell. Since the return fuel flow rate was typically over double that of the injected fuel flow, the fuel was cooled to maintain a day tank temperature below the flash point of the fuel. Depending on the temperature of the fuel being provided to the day tank from the main drum source, there was variation in the required return fuel temperature to maintain a safe operating range.

3.1.5 Motor Drive Power Output

The high pressure pump was driven by an electric motor through a variable frequency drive (VFD). This drive offered the ability to monitor power output to the motor from the VFD. While this does not take into account the impact of drive system losses, such as bearing friction or coupling inefficiencies, these losses can be expected to be small compared to pumping power and to remain consistent between tests. The measured power output to the motor is shown in Figure 27.

Over each test, there is a tendency for power to decrease over time. Since the only component that the motor is driving is the high pressure pump, it may be possible that high friction contact points were worn down over time resulting in more efficient operation.

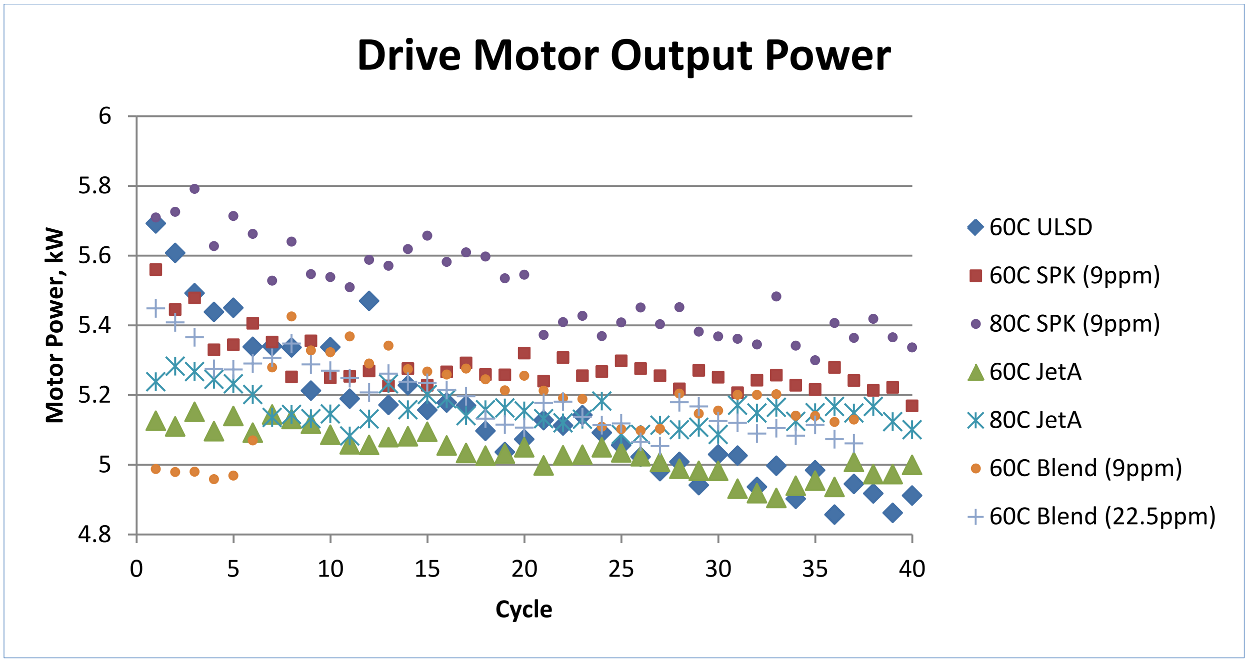


Figure 27. Drive Motor Power Output

3.1.6 Pump Bore

The condition of one pump bore is shown for comparison in Figure 28. Even the new pump condition had signs of polish, likely from performance checks during the manufacturing process. Throughout the seven tests, there was not a large difference in polished area despite the variations in lubricity and viscosity between fuels.

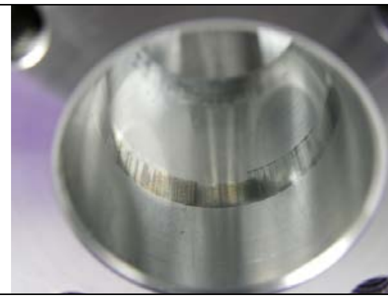
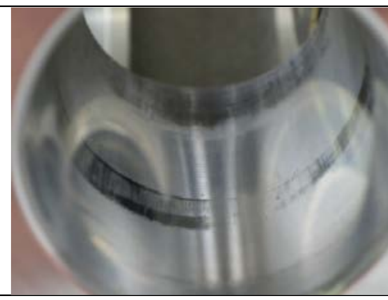
	
New and Unused	60°C Ultra Low Sulfur Diesel
	
60°C SPK	80°C SPK
	
60°C Jet A	80°C Jet A
	
60°C Blend w/ 9 ppm DCI-4A	60°C Blend w/ 22.5 ppm DIC-4A

Figure 28. Pump Bores

3.1.7 Pump Inlet Check Valves

The inlet check valve is a component which, if failure occurs, can prevent the pump from properly developing rail pressure. The two major failure modes are for the valve to stick closed and no longer open, or fail open in a way that prevents it from properly sealing. If failing closed, fuel will be unable to fill the pump head chamber and therefore no additional fuel will be supplied to the rail. In this case, the injectors will rapidly drain the remaining high pressure fuel supply to the point of system fault codes invoking an engine protection shutdown, or injectors failing to fire due to lack of actuation pressure. If failing open resulting in sealing failure, insufficient pressure will be developed in the pump head to overcome to rail pressure on the downstream side of the outlet check valve. Fuel will be forced back through the inlet valve into the pump body. Again, pressure in the rail will decrease until the injection process is stopped. The valve and seat area of the component is shown in Figure 29. The small dimple marks visible are from post-test measurements that were taken, not from operation.

Figure 29. Inlet Check Valve

To compare the impact each fuel had on the contact surfaces of this valve, the post-test distance between the two flat surfaces was measured. In poor lubricity fuels, this surface would be expected to experience wear and erosion of metal as the valve is repeatedly seated, similar to valve recession in an internal combustion engine. One difference in this case, is that the valve surface protrudes beyond the surrounding material rather than being set within it. This is illustrated in Figure 30.

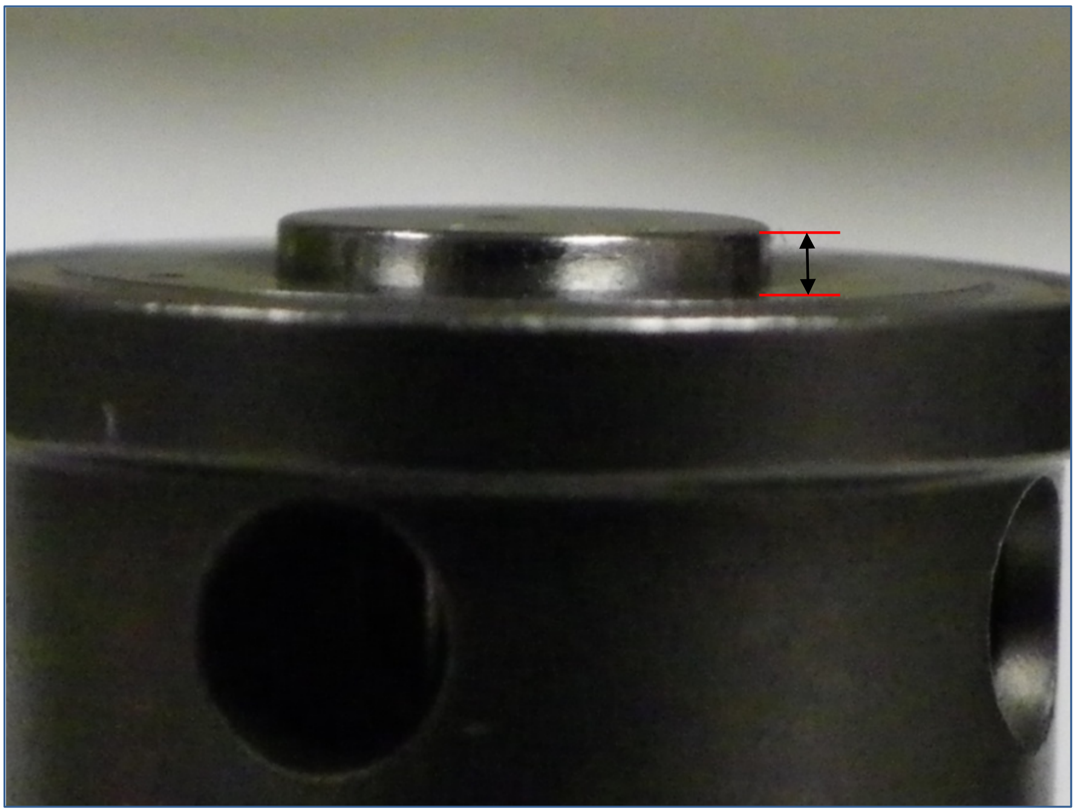


Figure 30. Inlet Check Valve Measurement

The size and geometry lead to difficulty in the measurement process for the component. Due to this, values obtained should be treated as indicators only rather than a fully traceable measurement. No measurement is available for the right valve of the 60°C Jet A test. During the installation of the 80°C Jet A pump, the threads became galled on the right pump head. The pump head, but not plunger or cam follower, was replaced with the 60°C Jet A component to allow testing to continue. Based upon the End of Test (EOT) measurements of the Jet A tests, this did not have a substantial impact on the check-valve as can be seen in Table 3.

Table 3. Inlet Check Valve Protrusion

Test	Left Valve, inches	Right Valve, inches
60°C Ultra Low Sulfur Diesel	0.0203	0.0199
60°C SPK w/ 9 ppm DCI-4A	0.0203	0.0209
80°C SPK w/ 9 ppm DCI-4A	0.0205	0.0209
60°C Jet A	0.0205	N/A
80°C Jet A	0.0200	0.0199
60°C Blend w/ 9 ppm DCI-4A	0.0205	0.0203
60°C Blend w/ 22.5 ppm DIC-4A	0.0206	0.0205

The variation of 0.001 in. between the largest and smallest measurements represents a 4.78% difference from test to test. There does not seem to be a strong trend between the EOT measurement and fuel viscosity or lubricity. The smallest observed value, 0.0199 inches, occurred in both the ULSD, best lubricity and viscosity, and high temperature Jet A, one of the lowest viscosity and lubricity tests.

3.1.8 Pump Shaft Bushings

A comparison of the end-of-test condition of the front shaft bushing is shown in Figure 31, including one from an unused pump as reference.

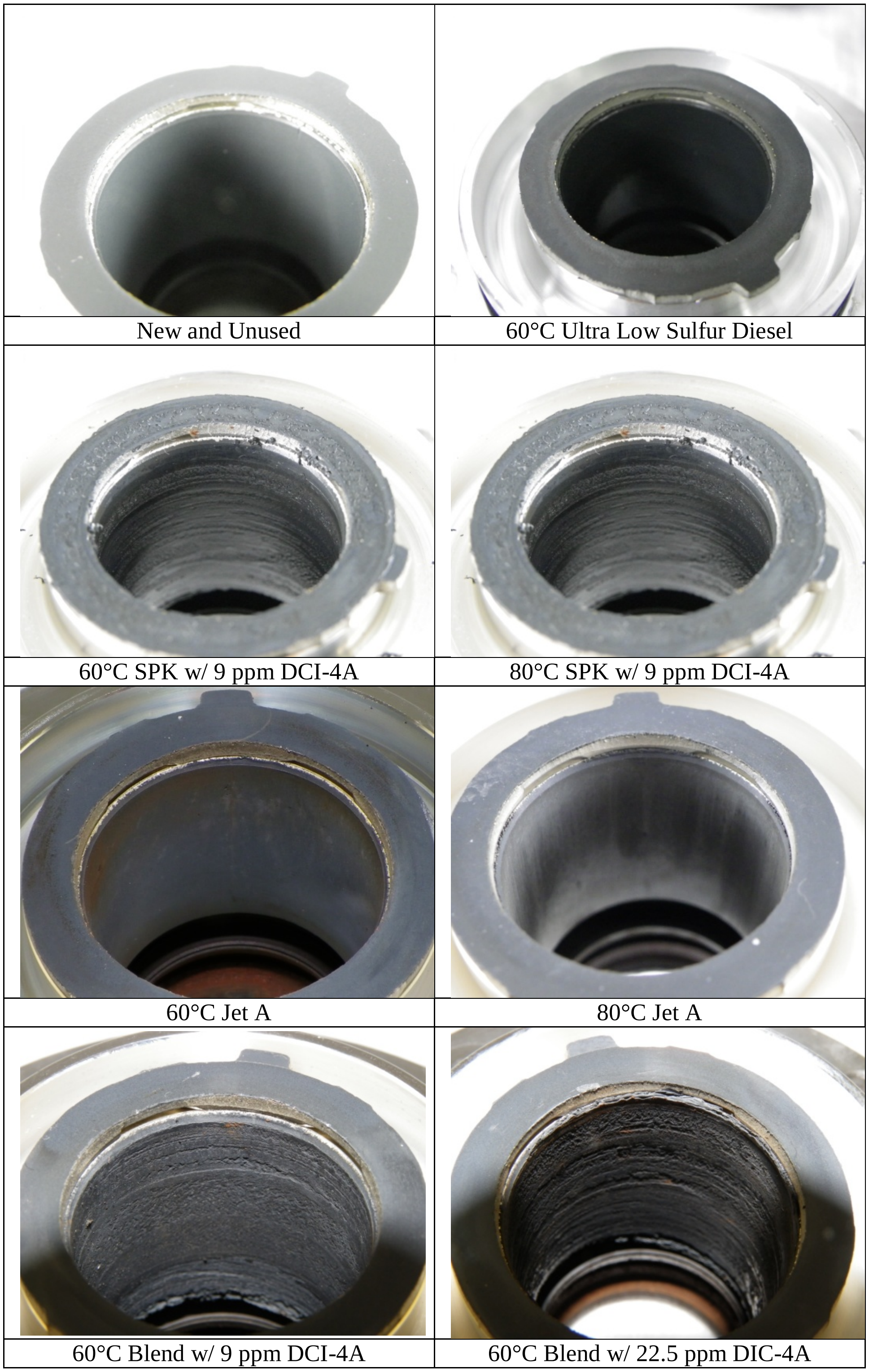


Figure 31. Pump Shaft Front Bushings

Following the two SPK tests, and the degradation witnessed, bushing inspections were conducted mid-test to monitor the rate at which the component was failing. This deterioration is shown in Figure 32.

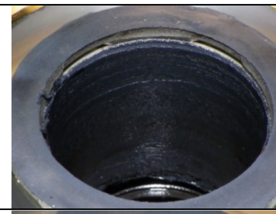
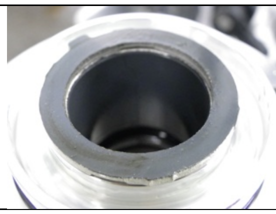
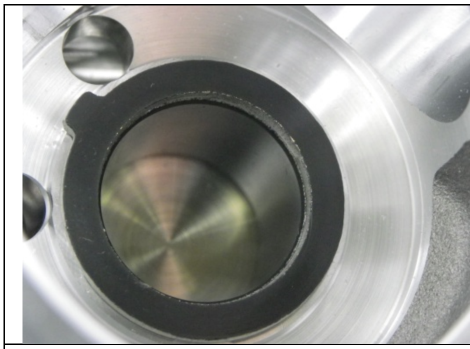
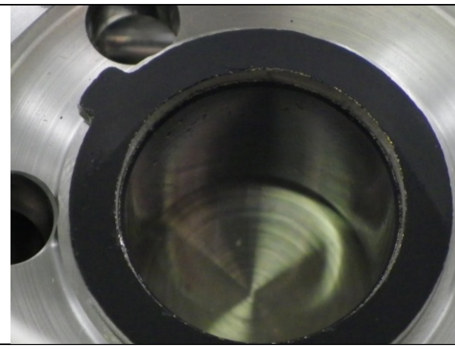
	60°C Jet A	80°C Jet A	60°C Blend w/ 9 ppm DCI-4A	60°C Blend w/ 22.5 ppm DIC-4A
100 Hours	N/A			
200 Hours				
300 Hours	N/A			
400 Hours				

Figure 32. Front Pump Bushing Deterioration Over Time

These inspections indicated that when damage was noted it typically occurred within the first 100 hours of the test. As bushing material was worn away from the shaft, the clearance between the two allowed for a greater fuel flow to pass through around the shaft to a return passage in the front pump cover. This was likely a contributing factor to the increased bypass and return fuel flow rates seen in Figure 26. The rear bushing within the pump body is shown in Figure 33.



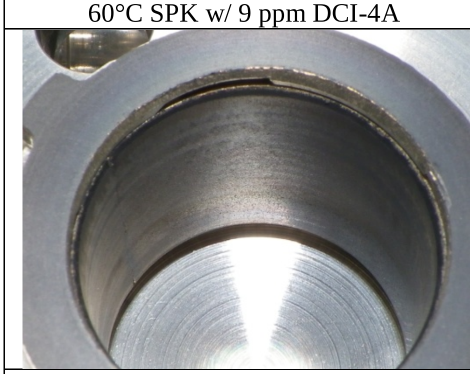
New and Unused



60°C Ultra Low Sulfur Diesel

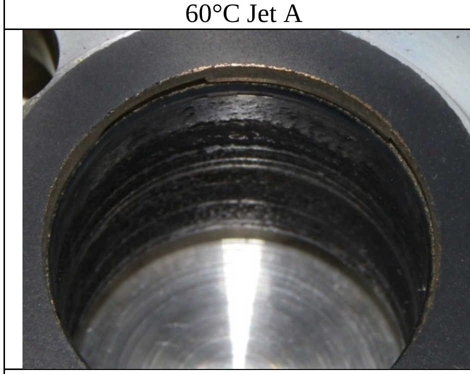
60°C SPK w/ 9 ppm DCI-4A

80°C SPK w/ 9 ppm DCI-4A

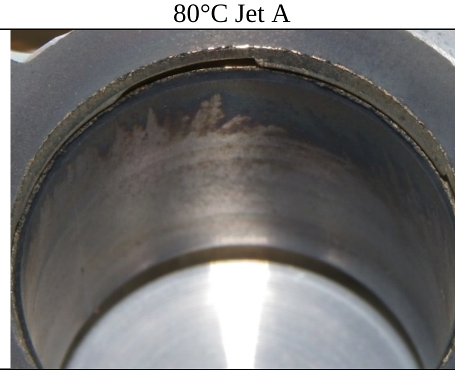


60°C Jet A

80°C Jet A



60°C Blend w/ 9 ppm DCI-4A



60°C Blend w/ 22.5 ppm DIC-4A

Figure 33. Pump Shaft Rear Bushings

The condition of the rear pump bushing was only inspected at the end of each test. While the front bushing condition varied from test to test, the rear pump bushing only experienced a major change in appearance during the high temperature SPK and 9 ppm Blend tests. Further investigation into the source of bushing degradation was conducted as part of Test #8 and showed that the root cause was likely not fuel related.

3.1.9 Pump Cam Shaft Lobe

The condition of the pump shaft lobes, shown in Figure 34, did not indicate a critical response to any of the fuels tested. Some discoloration was noted in the two 80°C tests, not unexpected based upon the temperatures and fuels being tested.

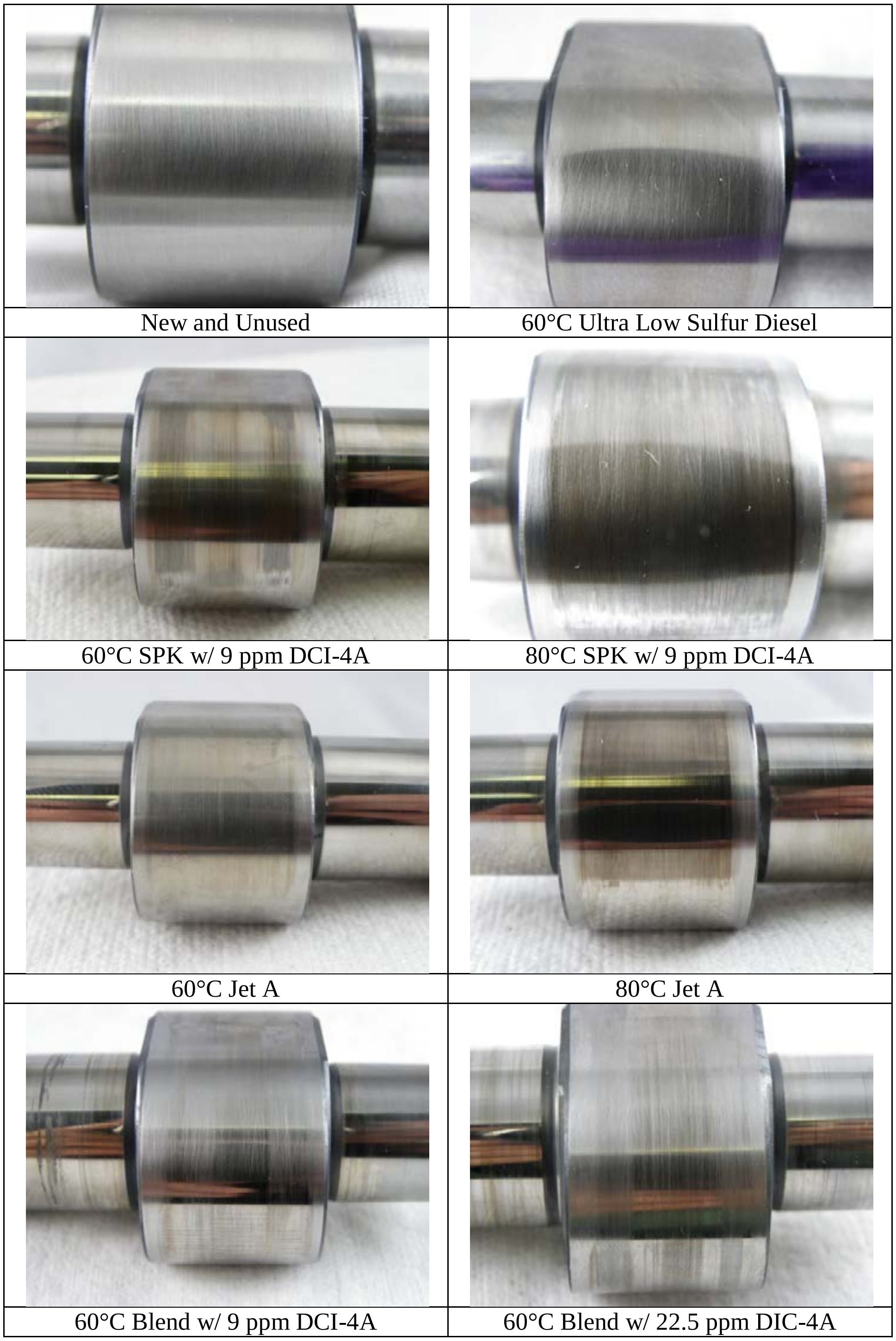


Figure 34. Pump Cam Shaft Lobe

In an attempt to quantify the impact of various fuels on cam lobe wear, the shafts from Test #1 (ULSD) and Test #8 (Jet A and SPK, see Pump Bushing and Injector Ageing Investigation (Test #8)) were precision traced to compare the "best" and "worst" fuels evaluated. Figure 35 and Figure 36 show the profile of the lobe at the point of highest contact pressure. Figure 37 is a trace off of a new cam lobe for comparison. Between the three figures, the waviness parameter varies from 1.81 to 2.03μm. The noise in the surface measurement, combined with the similar trace results, indicate that there is not a substantial amount of wear occurring on the pump camshaft lobes regardless of the fuel used.

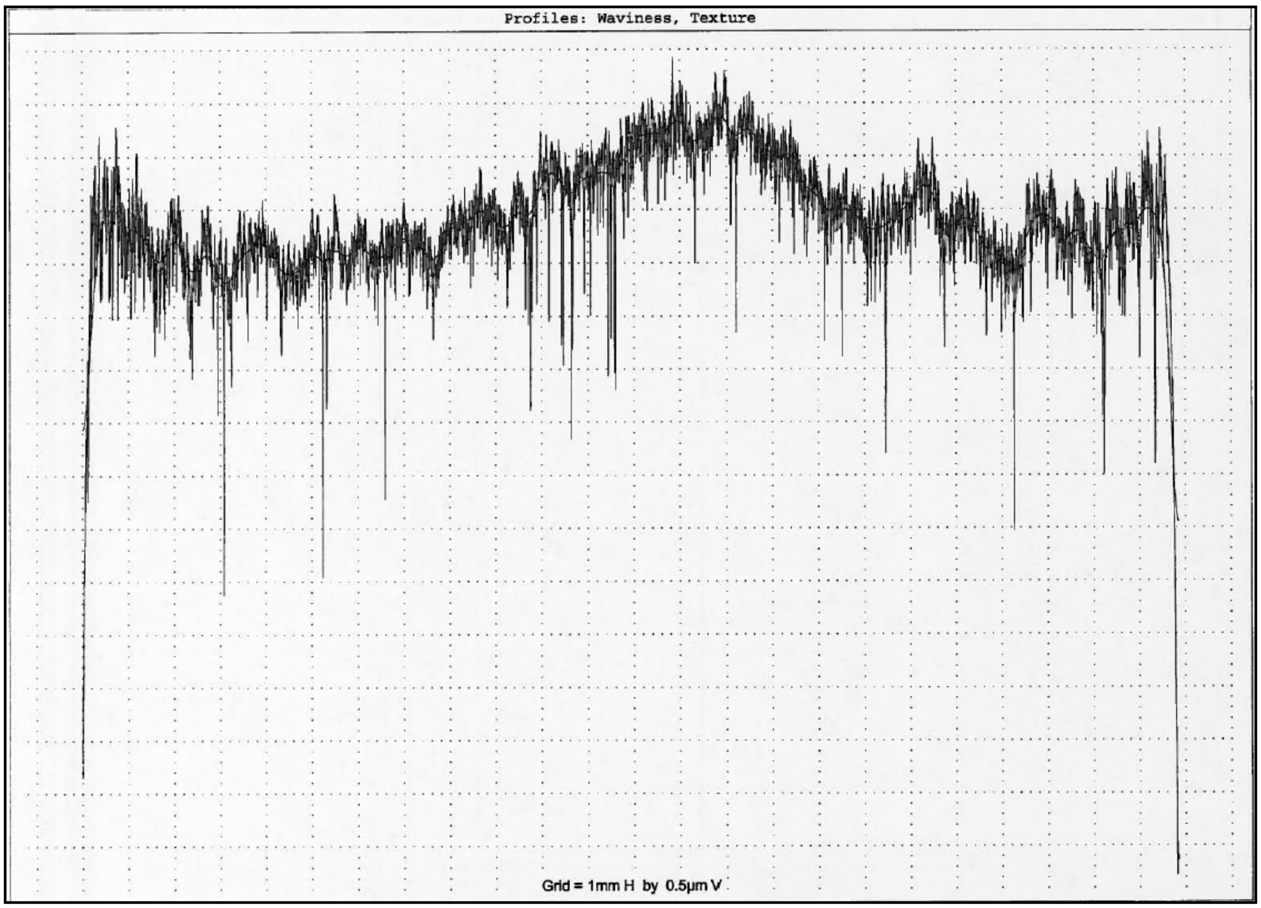


Figure 35. ULSD Cam Lobe Trace

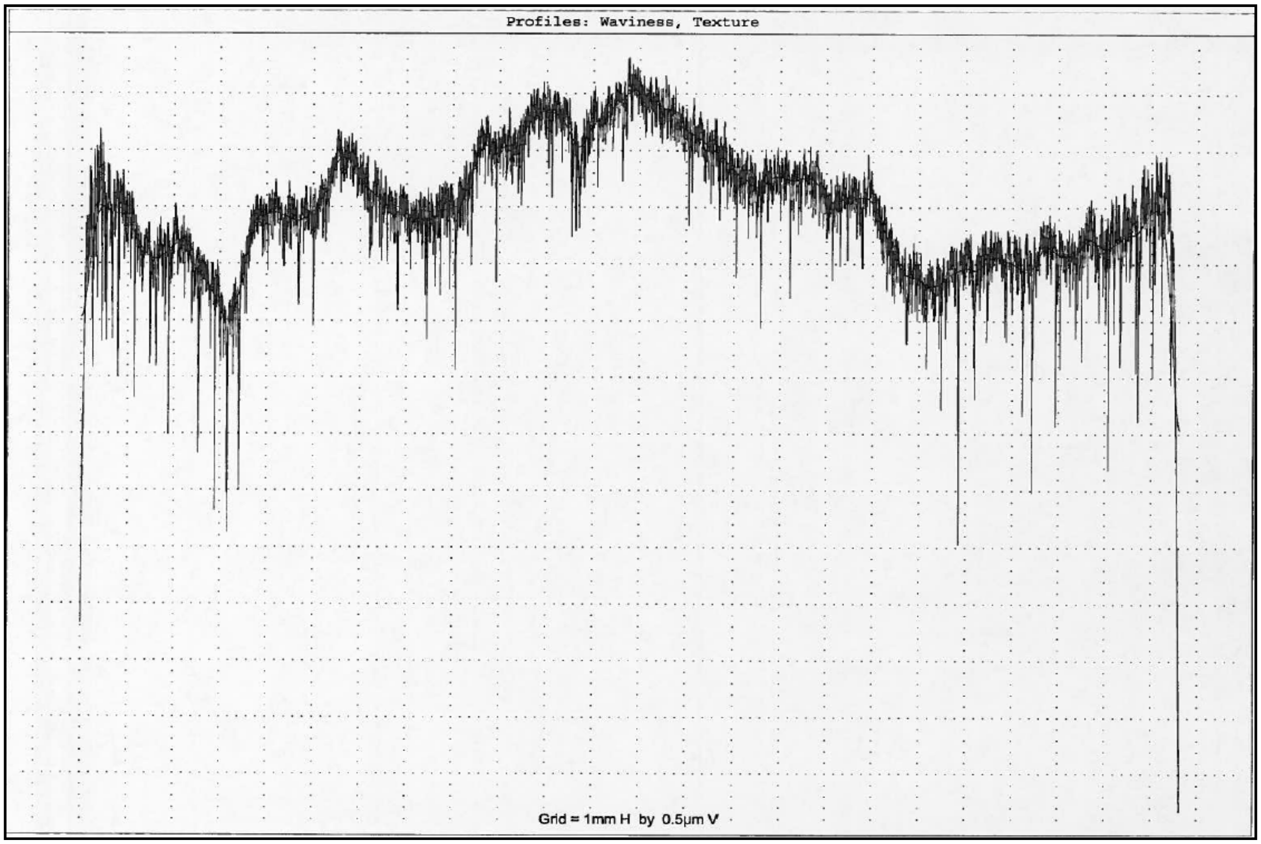


Figure 36. Test #8 Cam Lobe Trace

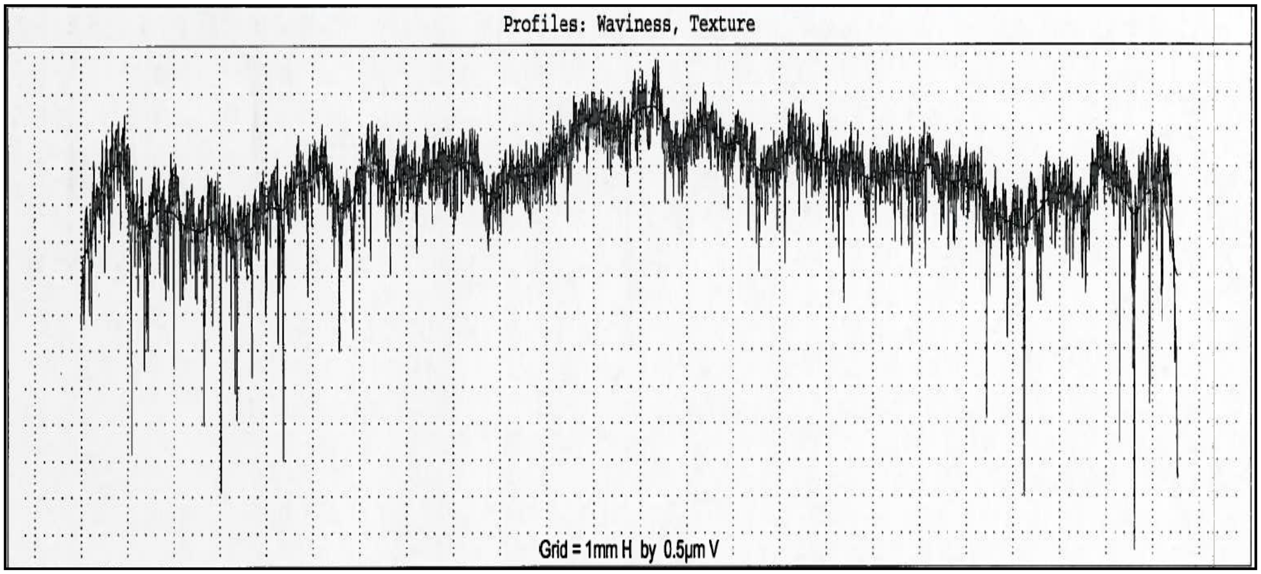


Figure 37. New Cam Lobe Trace

Figure 38 and Figure 39 show the surface roughness for the same location. The edges of the lobe, where the roller-follower does not travel, show a higher degree of roughness than the center of the lobe. This indicates that the cam lobe is being polished to a higher degree over the course of the test than in the original manufacturing process.

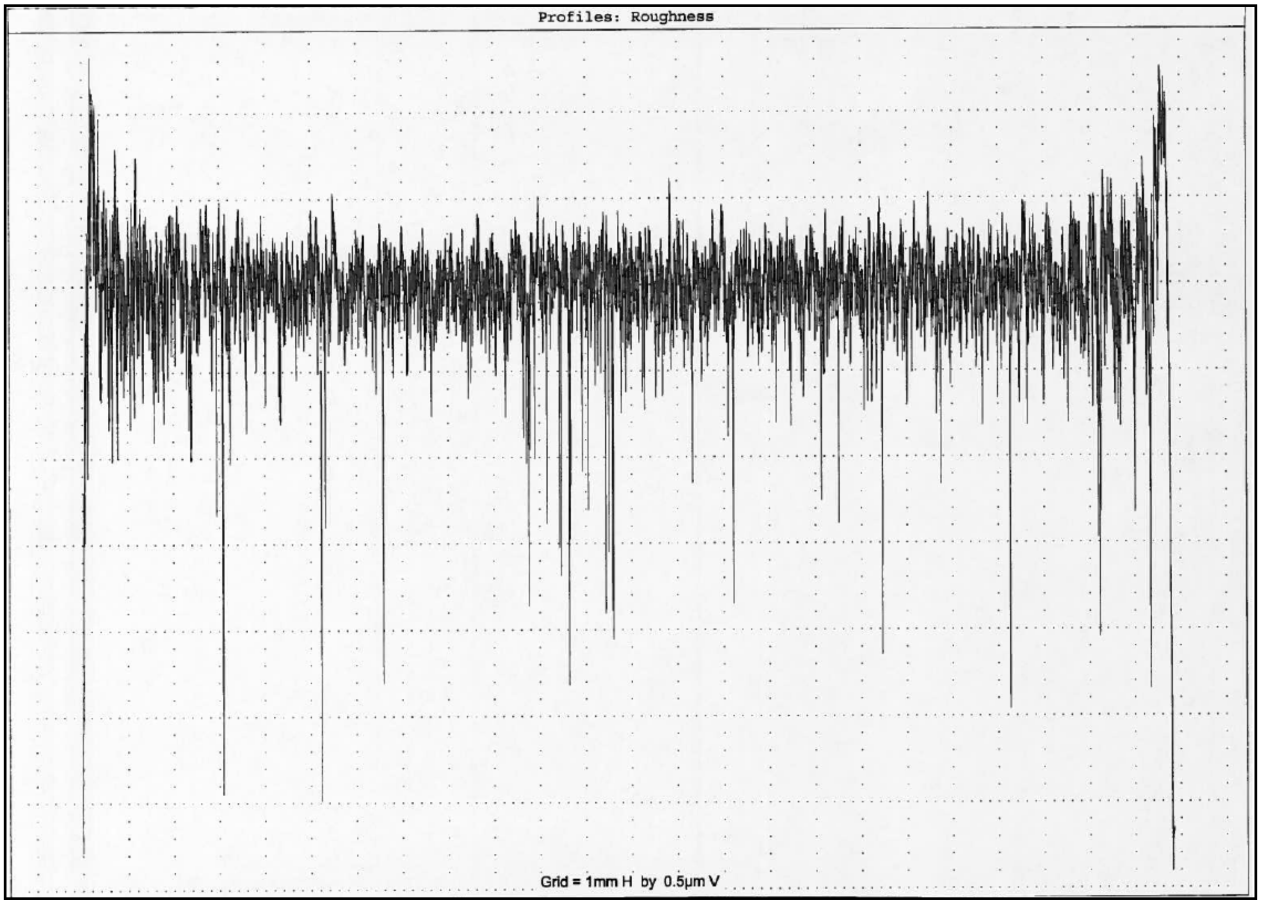


Figure 38. ULSD Cam Lobe Roughness

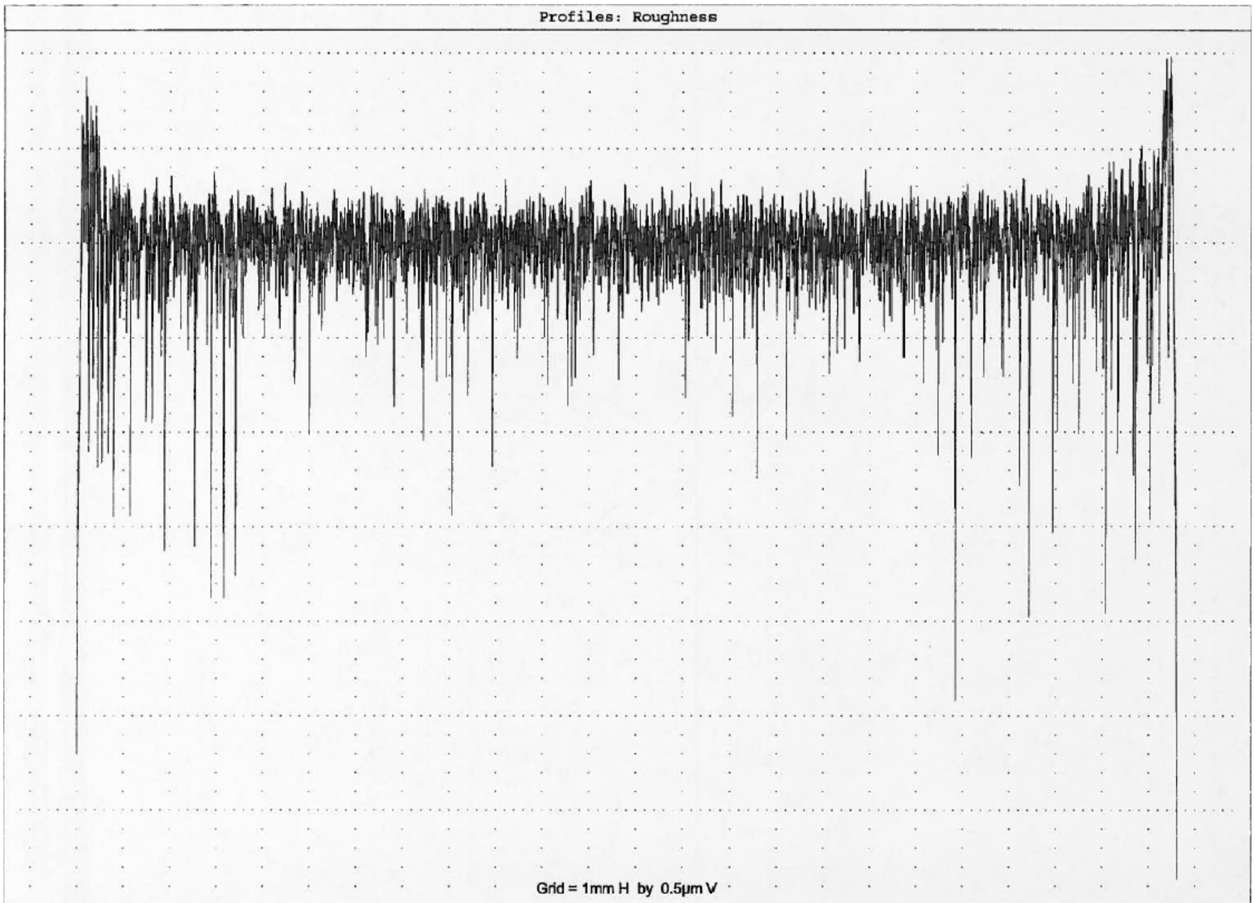


Figure 39. Test #8 Cam Lobe Roughness

3.1.10 Tappets

The condition of the roller-follower is shown in Figure 40, only one per test is shown. It should be noted that the follower is placed upside-down for photographing, and that the roller which contacts the cam lobe is located at the top of the images shown.

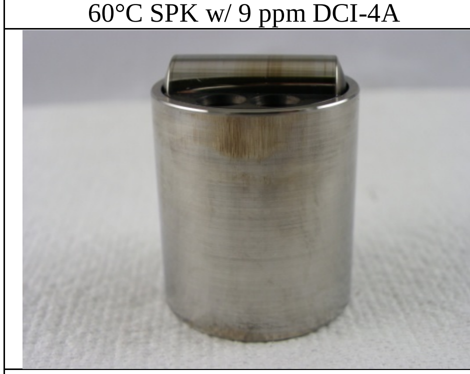
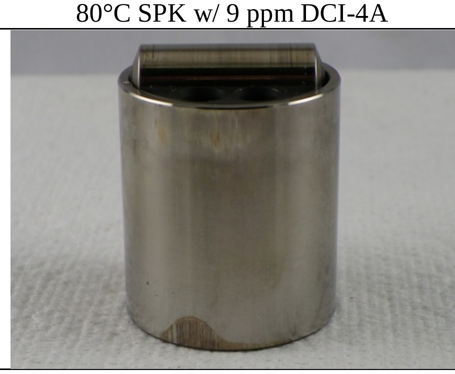
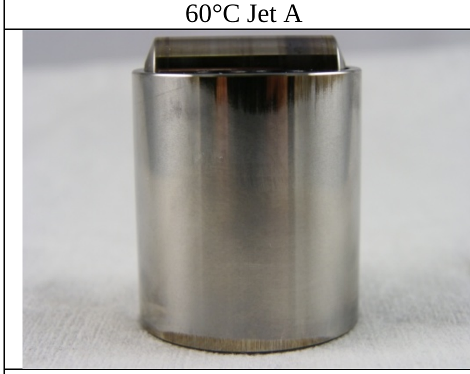
	
New and Unused	60°C Ultra Low Sulfur Diesel
	
60°C SPK w/ 9 ppm DCI-4A	80°C SPK w/ 9 ppm DCI-4A
	
60°C Jet A	80°C Jet A
	
60°C Blend w/ 9 ppm DCI-4A	60°C Blend w/ 22.5 ppm DIC-4A

Figure 40. Pump Roller Follower (Left)

The follower cup, made of steel, travels within the aluminum pump bore to reduce side loading on the high pressure plunger. From test to test, there is not a strong connection between the lubricity of the fuel and wear on this component. A polished area appears at the top and bottom of each cup parallel with the follower from where contact is made with the pump bore. Since there is enough gap for fuel to lubricate the sliding surface between the cup and pump bore, the cup is able to tilt and contact forces are concentrated at these polished areas. From a temperature perspective, both the SPK and Jet A tests show similar condition at high and low temperatures. Likewise, the Blended fuel at both 9 and 22.5 ppm DCI-4A produced a similar wear pattern.

3.1.11 Injector Needle Tip

The injector needle of the 6.7L engine is approximately 1.625 in. long and has a hardened coating on the tip to reduce wear. The triangular center section allows fuel to pass along the needle while it is guided in the injector tip bore. When not energized, the needle seats in the injector tip to stop the passage of fuel into the cylinder. An injector needle is shown for each test in Figure 41.

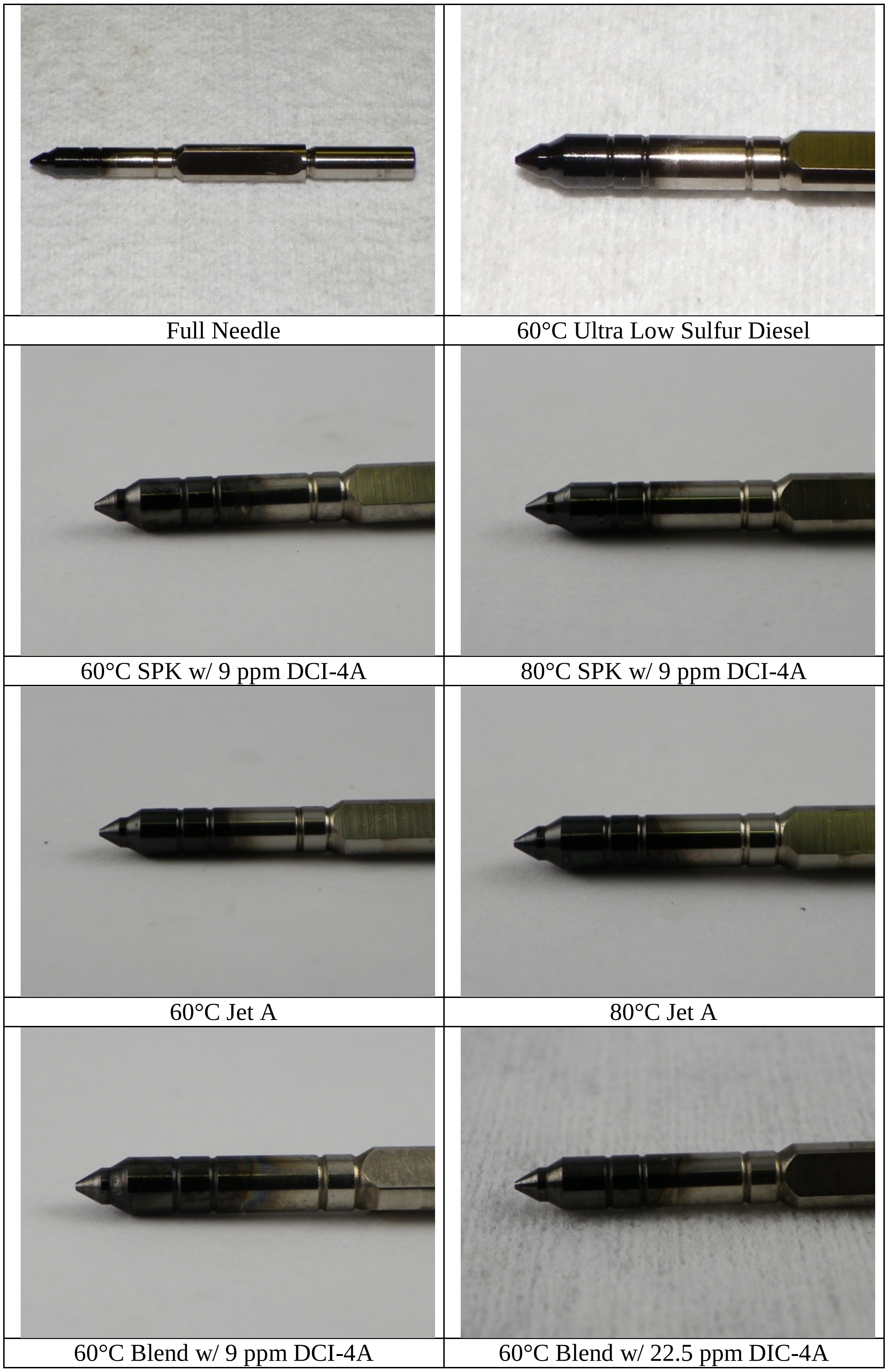


Figure 41. Injector Needle

3.1.12 Lower Hydraulic Coupler Piston

The lower piston of the injector hydraulic coupler is shown in Figure 42. This piston travels within the bore of the coupler to actuate the needle lift of the injector. The most noticeable mark on this component, clearly seen on the 80°C SPK image, is where an internal step within the coupler is located. As the injector is de-energized, the lower piston travels back into the coupler along this step, resulting in the scar shown.

The variation in wear pattern from one test to another does not trend well with lubricity or viscosity. In the case of Jet A, the elevated temperature, and decreased viscosity, produced almost no visible wear while the lower temperature test component was one of the most pronounced. Similarly, the two blended fuel evaluations showed a more pronounced wear scar with an increased level of lubricity improver. In no injector did the component exhibit indications that the selected fuel was impacting performance. All components were free from any signs of binding or sticking at the time of disassembly.

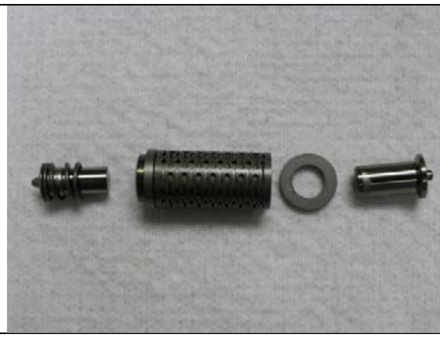
	
Component Location, Far Left	60°C Ultra Low Sulfur Diesel
	
60°C SPK w/ 9 ppm DCI-4A	80°C SPK w/ 9 ppm DCI-4A
	
60°C Jet A	80°C Jet A
	
60°C Blend w/ 9 ppm DCI-4A	60°C Blend w/ 22.5 ppm DIC-4A

Figure 42. Lower Hydraulic Coupler Piston

3.1.13 Upper Hydraulic Coupler

At the other end of the coupler is the upper piston which the piezo stack acts directly upon. This piston has a larger diameter than its lower counterpart to provide the linear motion amplification when the piezo stack is energized. A similar style of scar can be seen on the component in Figure 43 and Figure 44.

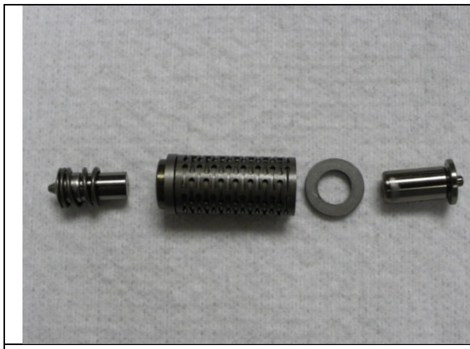
	
Component Location, Far Right	60°C Ultra Low Sulfur Diesel
	
60°C SPK w/ 9 ppm DCI-4A	80°C SPK w/ 9 ppm DCI-4A
	
60°C Jet A	80°C Jet A
	
60°C Blend w/ 9 ppm DCI-4A	60°C Blend w/ 22.5 ppm DIC-4A

Figure 43. Upper Hydraulic Coupler Piston, Site A

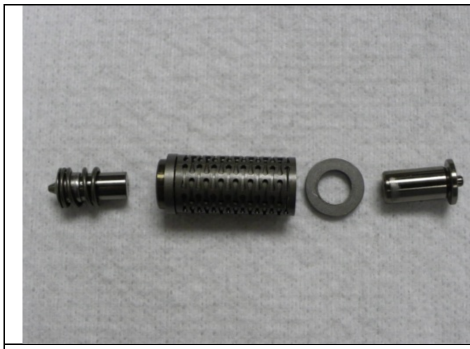
	
Component Location, Far Right	60°C Ultra Low Sulfur Diesel
	
60°C SPK w/ 9 ppm DCI-4A	80°C SPK w/ 9 ppm DCI-4A
	
60°C Jet A	80°C Jet A
	
60°C Blend w/ 9 ppm DCI-4A	60°C Blend w/ 22.5 ppm DIC-4A

Figure 44. Upper Hydraulic Coupler Piston, Site B

The upper component wear, on both sides, varied from the test to test but again did not seem to trend strongly with a fuel property. However, since the coupler is a critical component in the injector which could lead to a failure, and one of the few injector parts to have a visible wear scar, further quantitative methods were investigated to compare fuel impact. Guidelines from the CRC Distress Rating Manual 21 were used to evaluate the component from ULSD, 9 ppm Blend, and 80°C Jet A tests, representing a good, medium, and poor fuel based on lubricity. For each test, the component was removed from 7 of the 8 injectors. One injector was left intact and assembled in the event future inspection of an unhandled component was required. Merit ratings were given on a surface area percentage - rating basis for Site A, Site B and the remainder of the part (Site C). Results are presented in Table 4, Table 5, and Table 6.

Table 4. ULSD Upper Coupler Piston Ratings

AF7497-60C-ULSD FRD				
Injector	**Site A**	**Site B**	**Site C**	**Average Wear**
A	8% - 7.0	5% - 8.0	87% - 9.0	8
B	2% - 7.0	5% - 8.0	89% - 9.0	8
	4% - 8.0			
C	4% - 7.0	5% 8.0	91% - 9.0	8
D	5% - 7.0	3% - 8.0	92% - 9.0	8
E	6% - 7.0	6% - 8.0	88% - 9.0	8
F	7% - 7.0	6% - 8.0	87% - 9.0	8
G	7% - 7.0	4% - 8.0	89% - 9.0	8

Table 5. 9 ppm Blend Upper Coupler Piston Ratings

AF7824-60C-Blend9ppm FRD				
Injector	**Site A**	**Site B**	**Site C**	**Average Wear**
A	7% - 7.0	7% - 8.0	86% - 9.0	8
B	6% - 7.0	6% - 8.0	88% - 9.0	8
C	7% - 7.0	5% -8.0	87% -9.0	8
		1% - 7.0		
D	8% - 7.0	7% - 8.0	85% - 9.0	8
E	3% - 7.0	7% - 8.0	86% - 9.0	8
	4% - 8.0			
F	5% - 7.0	7% - 8.0	86% - 9.0	8
	2% - 8.0			
G	4% - 7.0	3% - 8.0	93% - 9.0	8

Table 6. 80°C JetA Upper Coupler Piston Ratings

AF8027-80C-JetA FRD				
Injector	**Site A**	**Site B**	**Site C**	**Average Wear**
A	3% - 7.0	7% - 8.0	90% - 9.0	8
B	2% - 7.0	8% - 8.0	87% - 9.0	8
	3% - 8.0			
C	7% - 7.0	3% - 8.0	90% - 9.0	8
D	7% - 7.0	8% - 8.0	85% - 9.0	8
E	7% - 7.0	8% - 8.0	85% - 9.0	8
F	1% - 7.0	2% - 8.0	96% - 9.0	8
	1% - 8.0			
G	9% - 7.0	6% - 8.0	85% - 9.0	8

After evaluating the three tests, it was determined that results were inconclusive based upon this methodology. Within a given set of components, the variation in size and severity of the wear scar resulted in an average wear merit rating (10 for a new component, 0 for failed component) of 8 for each component inspected.

3.1.14 Pump Bushing and Injector Ageing Investigation (Test #8)

With the variation seen in the front bushing of the high pressure pump, a final test was devised in an attempt to classify the bushing failure as either a fuel related or installation issue. Since bushing degradation was only observed when the SPK fuel was present, both neat and blended, it was unknown if a property of the synthetic fuel other than lubricity or viscosity was at fault. The other possibility considered was that the failure was the result of the pump installation rather than a fuel effect. Prior to the final test, it was noted that the clearance between the drive hub and front pump cover differed from test to test. On a number of the tests which showed bushing degradation, there was also an appearance of wear on the outside of the pump cover. A comparison of this is shown in Figure 45.

End of Test 60°C Blend w/ 22.5 ppm DIC-4A	End of Test #8 (Jet A and SPK)

Figure 45. Front Plate External Wear

If the hub had started those tests rubbing against the aluminum of the plate, the heat produced may have been enough to damage the bushing material. Since the failure formed early in the test, when it occurred at all, it would be reasonable to conclude that once enough material had been worn away the excess heat developed from friction would cease and the bushing condition would stabilize. To test this, the final pump was tested on Jet A and SPK base fuels, both clay treated to remove all additives from the project at an inlet temperature of 60°C. The removal of all additives from the fuel increases the severity of the test by eliminating any lubricity improvers such as DCI-4A. The surface of the drive hub was machined to prevent any possibility of interference with the front pump plate. After 200 hours operation with Jet A the bushing was inspected and fuel source changed to SPK. While the goal was to run the pump for 200 hours with SPK, failure in another area of the pump caused a premature end of testing. The condition of the bushing at different intervals throughout the test can be seen in Figure 46.

New and Unused	200 Hours Jet A	163 Hours SPK, 363 Hours Total

Figure 46. Test #8 Bushing Condition

The condition of the bushing did not have a substantial change through the test despite the use of fuel with a more severe ASTM D5001 BOCLE results than had previously been tested. The condition of the interior bushing and lack of external wear with the modified hub indicate that the issues previously seen on some fuels were related to physical installation rather than a fuel property such as lubricity or viscosity.

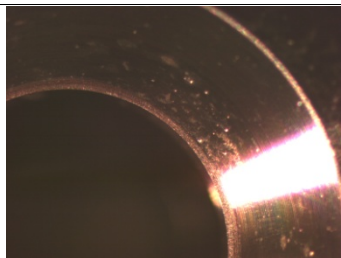
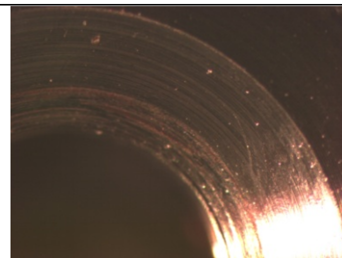
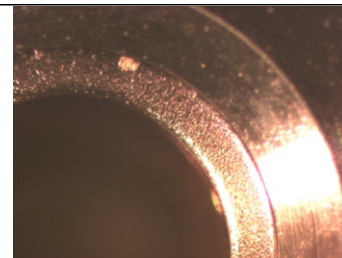
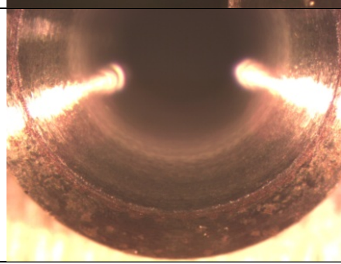
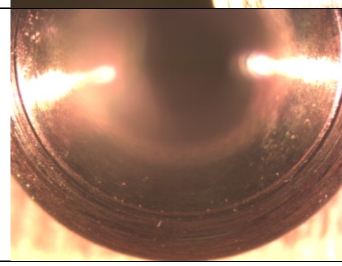
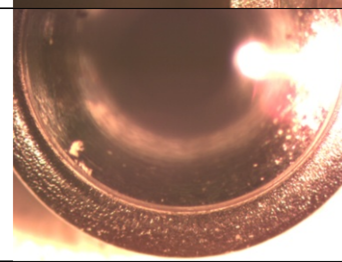
The area of the pump to experience failure, and prematurely cause an end of the test, was the inlet check valve (Figure 9). Throughout the test, two sets of check valves were used. When the first set failed it was unknown if this was an isolated incident, since it had not previously been observed, or test related. This occurred after 150 hours of operation on the clay treated Jet A fuel. Upon removal, the valves were noted to be "sticky" and did not open smoothly. The measured protrusion, discussed previously in Table 3, over time with the two test fuels are shown in Table 7.

Table 7. Test #8 Inlet Check Valves

Component Set	Left, inches	Right, inches
Set #1, 150 Hours Jet A (Failed)	0.0100	0.0108
Set #2, 50 Hours Jet A	0.0164	0.0161
Set #2, 50 Hours Jet A + 100 Hours SPK	0.0154	0.0154
Set #2, 50 Hours Jet A + 163 Hours SPK (Failed)	0.0150	0.0129

An examination of the valve seat area was conducted to determine the condition in both the failed components and those from other successful tests. For comparison, the ULSD and 80°C Jet A tests were selected. A comparison can seen of the valve seat and valve tulip areas in Table 8. The interaction area for the ULSD and 80°C Jet A tests shows some signs of sliding contact between valve and seat, however the protrusion measurements (Table 3) indicate this is mainly superficial and did not results in valve recession. The Test #8 component shown has a distinctly different surface appearance on both the seat and tulip areas.

Table 8. Inlet Valve Comparison

	ULSD	**80°C Jet A**	**Test #8 Set #1**
Component Use	400 Hours	400 Hours	150 Hours
Valve Seat			
Valve Tulip			

Additional magnification of the failed component is shown in Figure 47, pitted unlike those surfaces seen in other evaluations. The texture is not what would typically be expected of wear due to poor lubricity fuel and sliding contact. It is possible, based upon the physical design of the pump, that the seat could have been impacted by the pump plunger, in some ways similar to valve impaction on a piston top in an engine overspeed event. Unfortunately, it is impossible to determine this without additional testing to isolate the root cause.

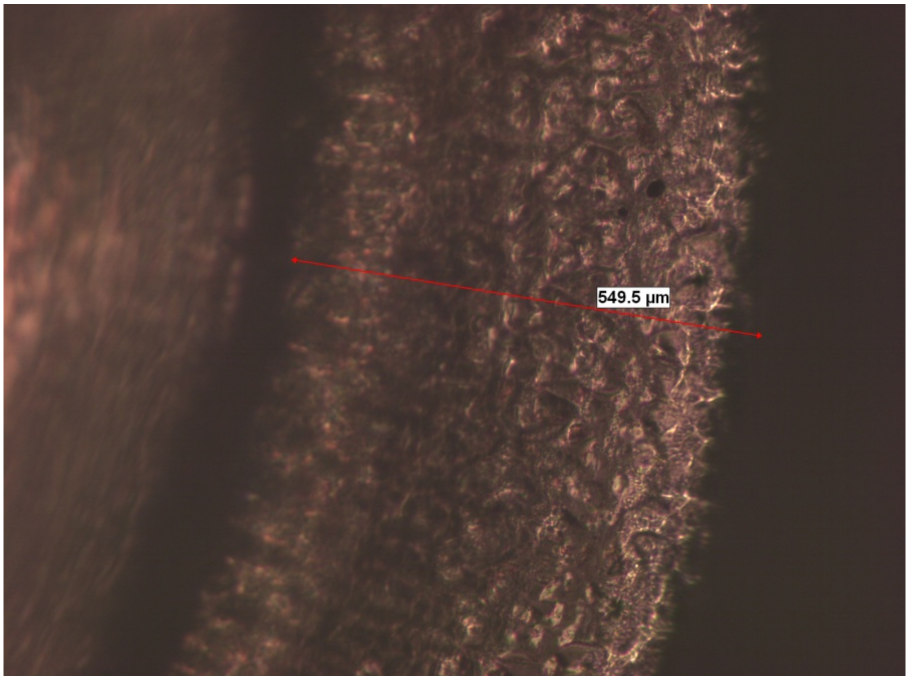


Figure 47. Test #8 Tulip, 100x Zoom

In addition to the using Test #8 to determine the cause of the bushing degradation in the pump, the injectors for the test were evaluated for performance changes over time in a fired engine. The same Jet A fuel used in pump stand testing was used to conduct fired engine full-throttle power curves. Additional points were added to cover all 10 modes of the NATO cycle. The engine was measured for power, efficiency, emissions output, and internal PCM control settings. Testing was conducted with new injectors, the same injectors aged for 350 hours with Jet A, and after 163 hours of use with SPK fuel. By testing the injectors in both fuel-system only and fired engine stands, the impact of injector ageing could be decoupled from performance shifts due to wear in the rest of the engine. Additionally, the use of the same injectors in fired engine and pump stand operation helped to confirm the validity of pump stand operational data taken through the PCM service tool. The engine used for this investigation was a MY2011 6.7L Export Engine, meaning the EGR system and all exhaust after treatment devices were removed. The PCM calibration file controlling operation was identical to that used for the bench stand.

Figure 48 shows the power and torque output of the engine for the three injector evaluations. In addition to the full throttle curve, a test point of 1,680 rpm and half throttle was added to replicate Mode 10 of the NATO cycle. While experiencing 513 hours of operation on fuel with no lubricity improver additive, the injector impact on engine power output was minimal.

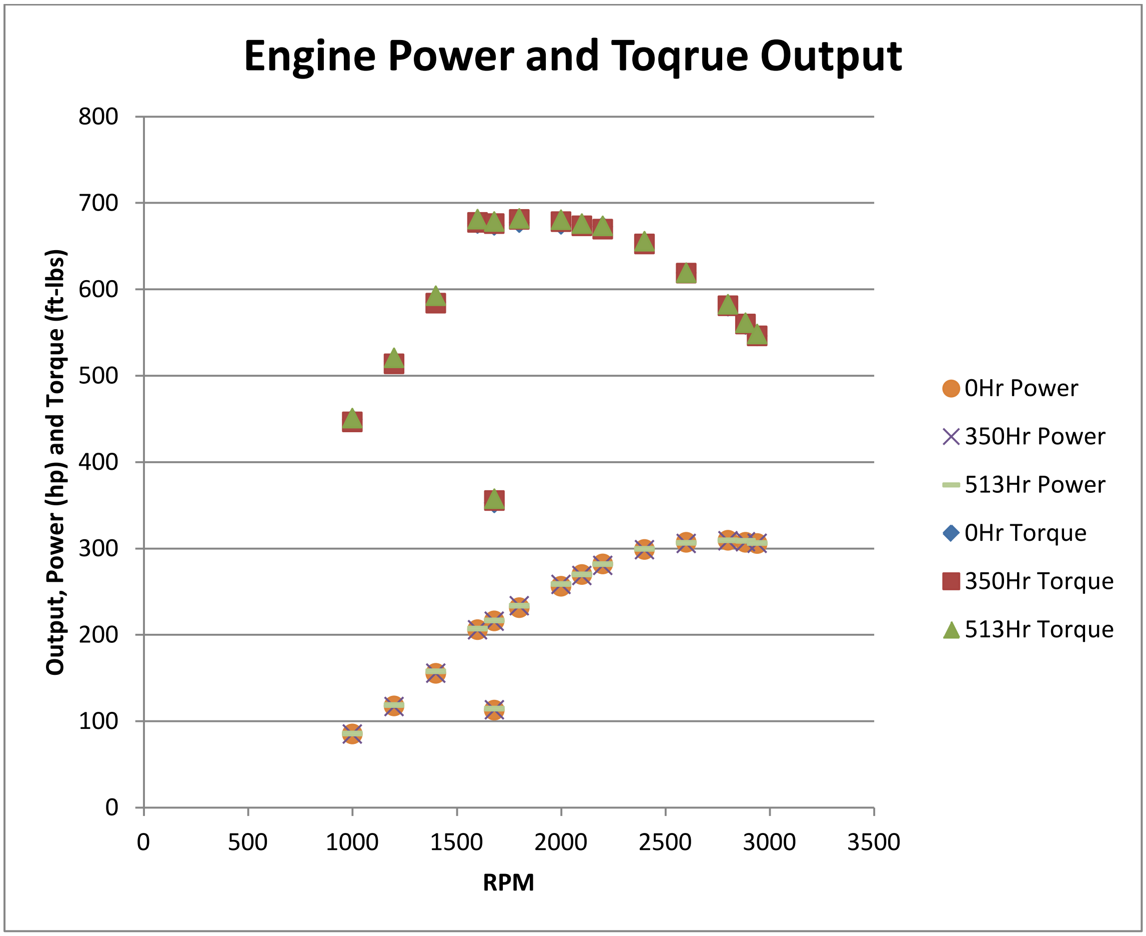


Figure 48. Engine Power and Torque Output

Along with a stable power output, the aged injectors did not have a negative impact on emission levels as can be seen in Figure 49 Figure 50. In the case of Carbon (CO) output, there was a slight reduction over time at the higher power outputs. Nitrogen Oxides (NOx) remained mostly stable throughout all three of the tests.

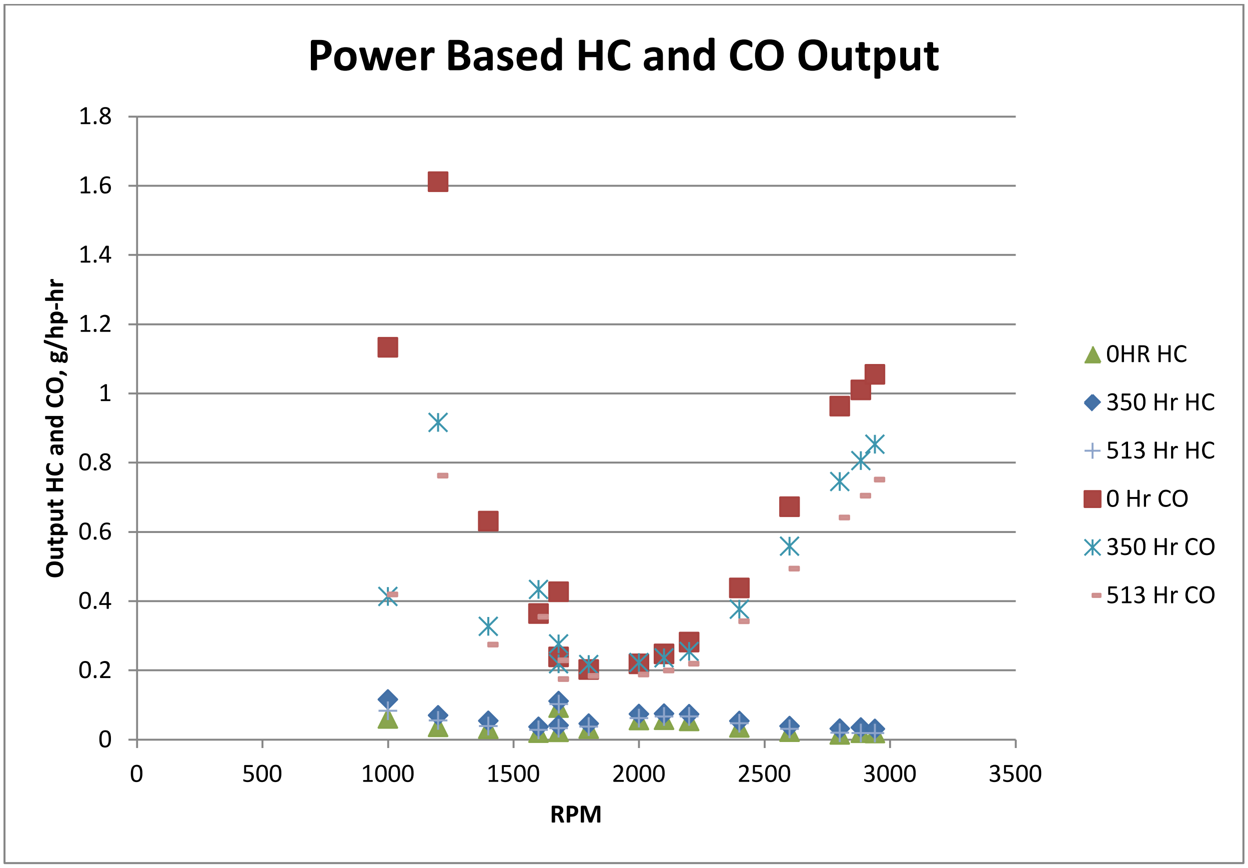


Figure 49. Engine Hydrocarbon and CO Output

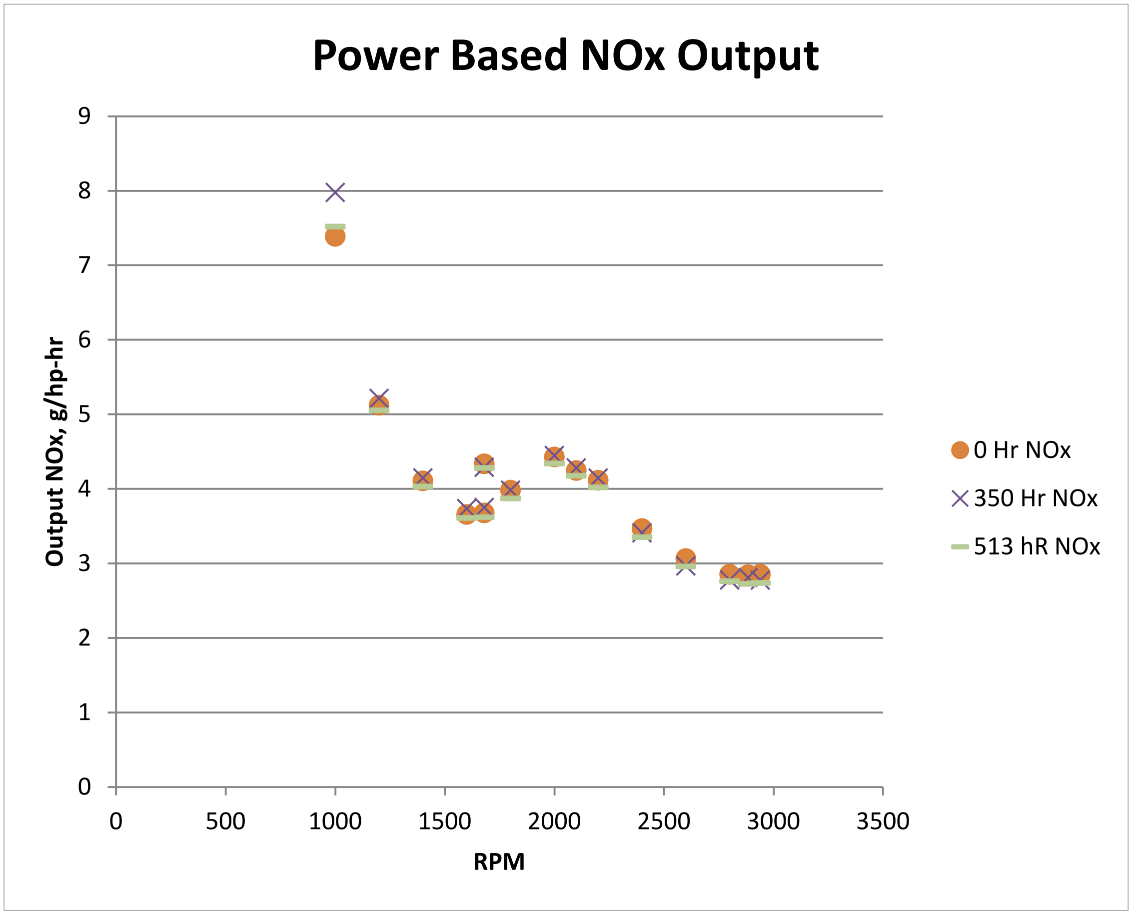


Figure 50. Engine NOx Output

To confirm that operation on the bench rig was consistent with that seen in a fired engine, a number of control parameters were tracked with the system service tool. Due to the nature of this real-time tool, reported values were taken as specific points rather than averaged over a longer duration, leading to some potential for discrepancy between readings. Because of this, PCM based data should be viewed for information purposes only.

The PCV and VCV duty cycle gives an indication of the overall system health and can be seen in Figure 51. Operation of the PCV differs only at two places where throttle actuation was also slightly different. VCV duty cycle follows very closely between pump stand and engine operation.

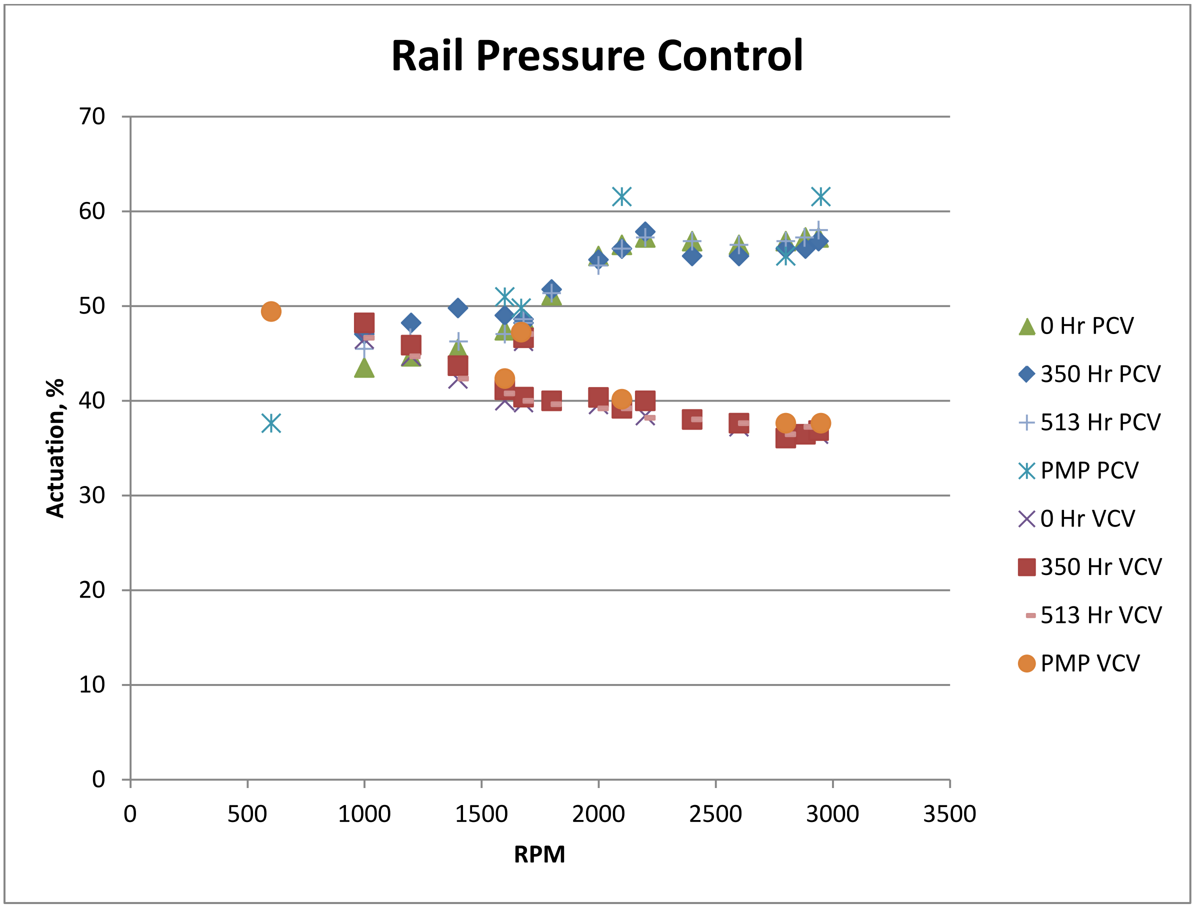


Figure 51. Rail Pressure Control Actuation

The PCM calculates a fuel flow rate based upon the rail pressure and injector needle actuation. For all full throttle points (rated power, peak torque, and 75% speed), the pump stand and engine data are in agreement as can be seen in Figure 52. For the partial load point at 1,680 rpm there was some discrepancy due to the variation in throttle actuation without torque feedback on the pump stand.

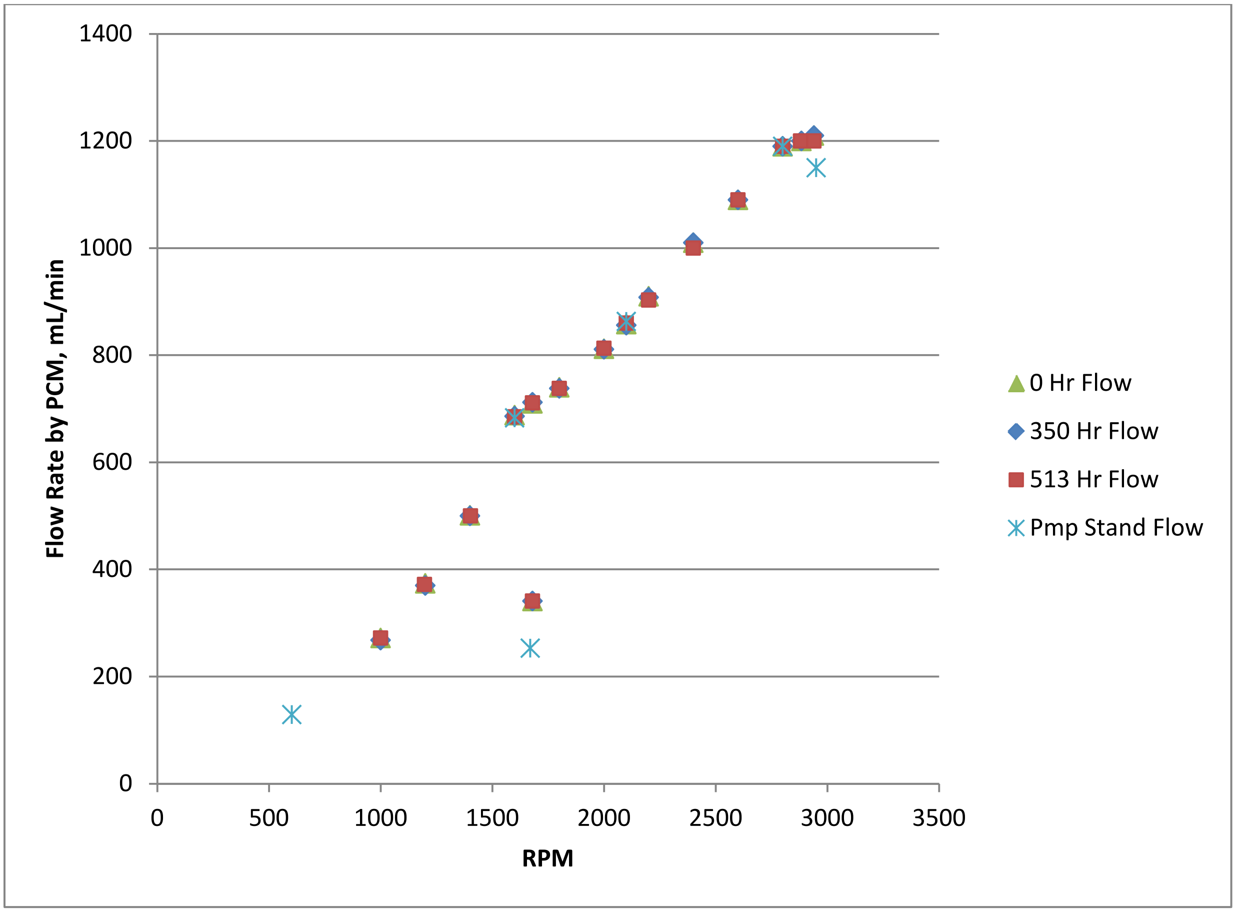


Figure 52. PCM Based Fuel Flow Rate

Figure 53 shows the injector trim angle in degrees before top-dead-center. Once again, the injectors maintained consistent performance between the three fired engine evaluations as well as pump stand operation. The two points in which pump stand injector trim do not fall in line with those of the engine are due to throttle actuation without closed loop torque feedback.

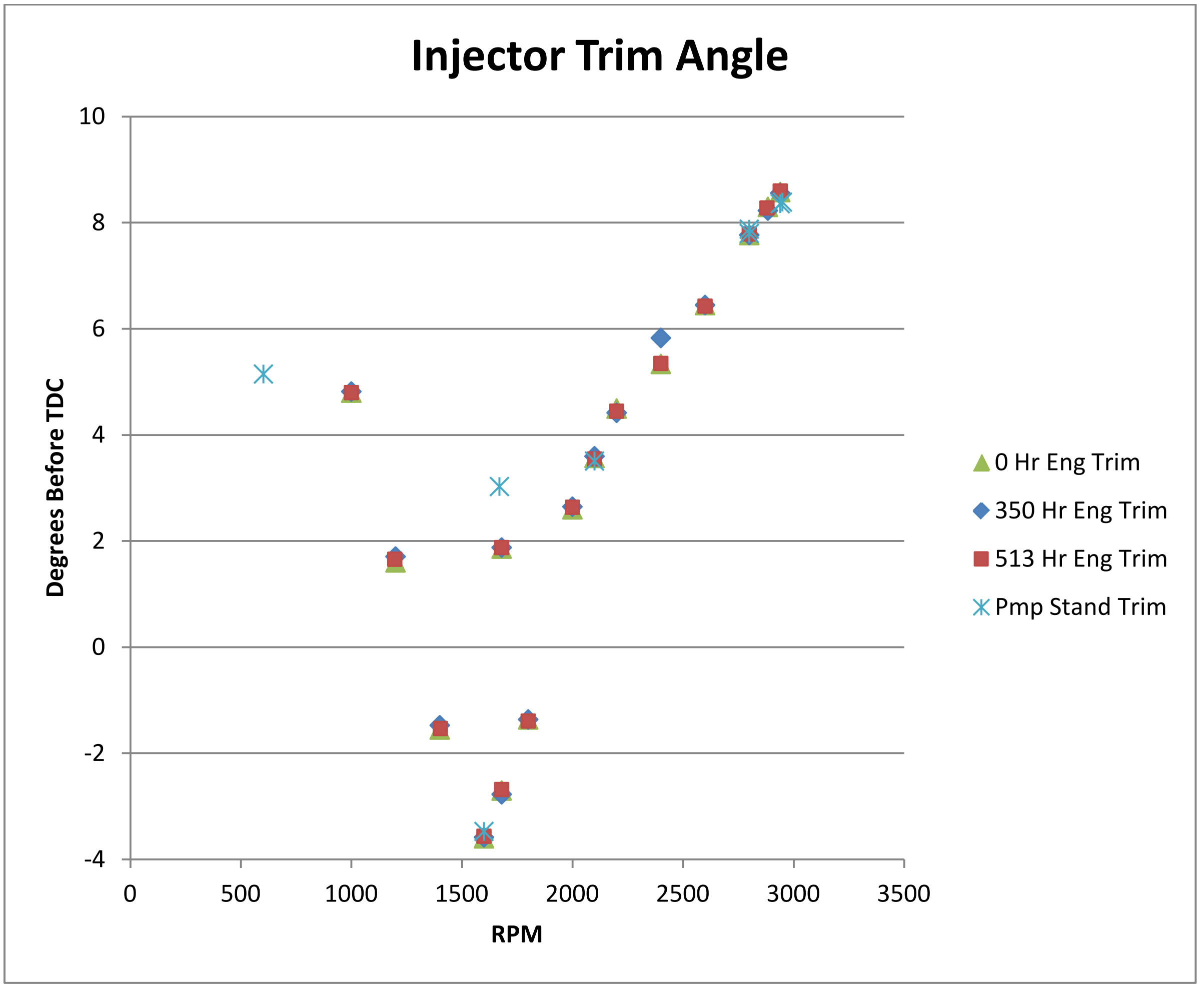


Figure 53. Injector Trim Angle

4.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Despite the low lubricity and viscosity characteristics of some of the test fuels when compared to ULSD, the system performed well from a durability standpoint and end-of-test component conditions showed no signs of imminent failure. This reinforces the performance seen with military fuels in other fired engine testing using the 2011 Ford 6.7L Diesel[4]. It should be noted that while no issues were captured in this testing, longer duration operation may locate critical areas not reached.

With the design of the HPCR fuel system, a certain amount of drift in pump performance can be masked by the buffer effect of the fuel rail. In this way, vehicle operation may continue without noticeable change to the operator while component degradation is occurring up to the point of catastrophic failure. Due to this, and the lower fuel requirements of pump stand operation, it is recommended that future testing of HPCR systems be extended out through 1,200 or more hours or until some change in injector performance can be noted.

Reliable measurement of injectors was shown to be possible using a fired engine in conjunction with the fuel system rig. The consistency of emissions output and ECM control indicated that over the 513 hours of operation no fuel related impact occurred. While the sample set for performance checking bench rig aged injector in the fired engine is small, the results have appeal as a cost effective way to check more than total fuel flow.

From the observable information, no negative impacts should be expected from the use of current military fuels with the 6.7L injection system, or even future blended fuels with adequate levels of lubricity improver. In the future, it may be beneficial to determine what, if any, the critical level of additive is to facilitate operation on neat SPK or other synthetic aviation fuels. In final conclusion, all available data indicates the 6.7L fuel injection system to be robust with regards to the selected synthetic and petroleum based fuels.

5.0 REFERENCES

1. ASTM Standard D6079, 2011, *"Standard Test Method for Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig (HFRR)1,"* ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/D6079-11

2. ASTM Standard D5001, 2010, *"Standard Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)1,"* ASTM International, West Conshohocken, PA, 2010, DOI: 10.1520/D5001-10

3. ASTM Standard D445, 2011, *"Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)1,"* ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/D6079-11

4. Brandt, A.C., Yost, D.M., *"Evaluation of Military Fuels Using a Ford 6.7L Powerstroke Diesel Engine,"* Interim Report TFLRF No. 415, August 2011, ADA560574.

APPENDIX A.

TEST STAND CONFIGURATION

The test stand, with components installed is shown in Figure A-1.

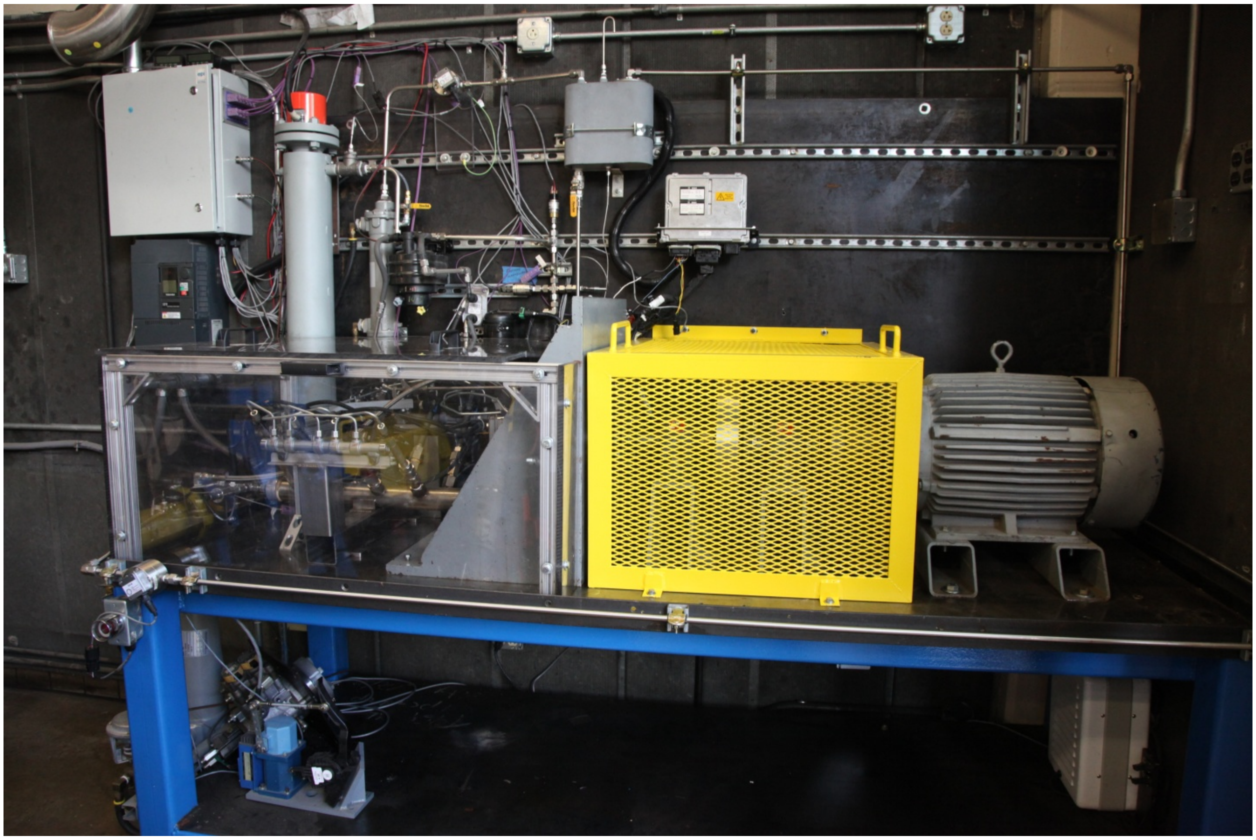


Figure A-1. Test Stand Installation

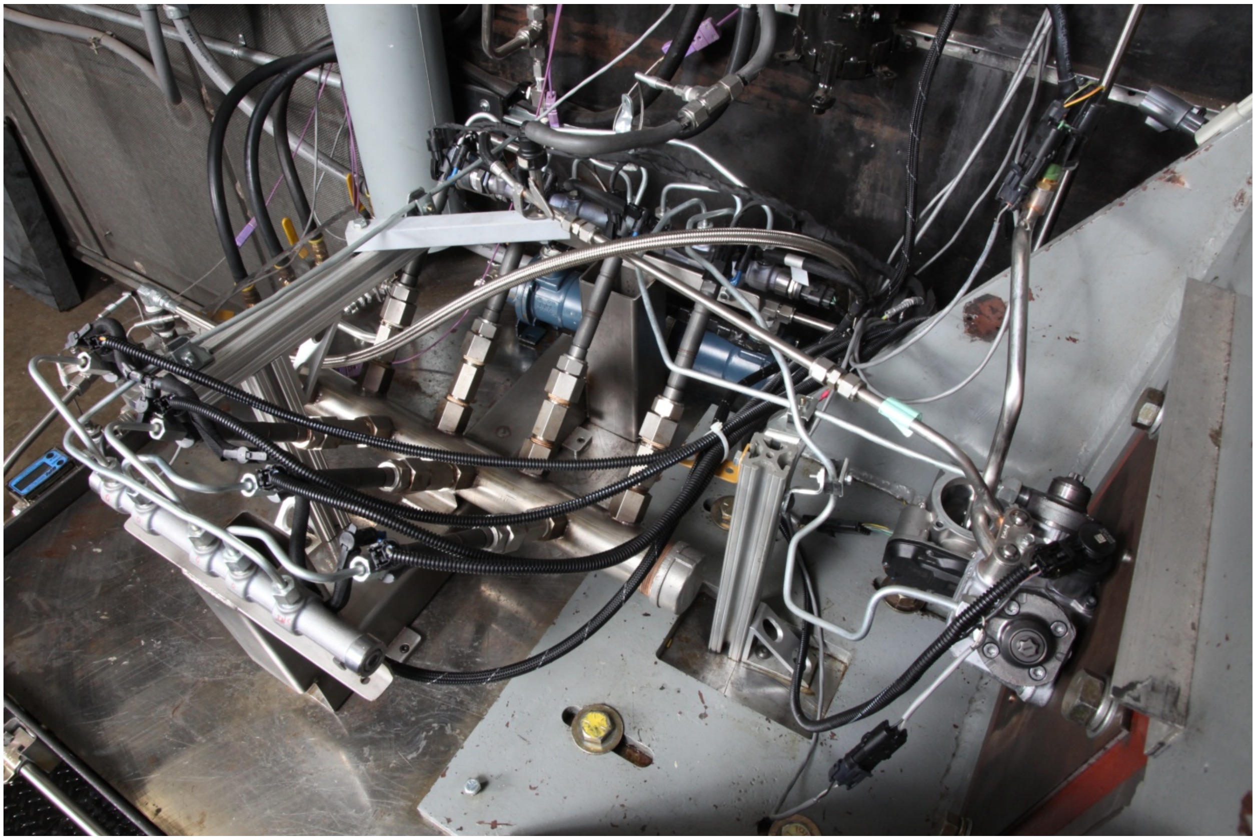


Figure A-2. Ford 6.7L Pump Stand Close Up

The table consists of two 8’x3’ steel plates and a ¼” mounting plate against the wall behind. The test pump was driven by a 25hp electric motor controlled via a variable frequency drive. The motor output connected through a Magnaloy Series 600 coupling to a main drive shaft. Supported by two pillow block bearings, the drive shaft held the 14in x 2in flywheel and drove a secondary shaft with timing equipment. The pump connected to the other end of the drive shaft with a Zero-Max 6A52 coupling. Fuel entered the test cell via stainless lines from a remote drum. A pressure regulator controlled the supply to the on-stand day tank at no more than six psig. This prevented the float valve in the day tank from being over pressurized and spilling. The fuel temperature at the inlet to the test parts was controlled using a circulation heater. Based upon the outlet temperature of the fuel from the heater, the power to the heater was adjusted to obtain the desired value. After injection, the hot fuel was routed through a liquid-to-liquid heat exchanger with the fuel entering the heater to allow the day tank temperature maintained lower. With pre-heated fuel entering the heater, the electrical burden of the stand was lowered. Injected flow was then cooled to a constant temperature before flow measurement. After flow was measured, the fuel was routed back to the remote drum rack. Bypass and return fuel was also measured for flow and cooled before being returned to the on-stand day tank. The heat exchanger for this fuel was controlled to maintain an elevated, but below flashpoint, temperature within the day tank. Speed signals, for both the system PCM and data acquisition software, came from a 3600 pulse-per-revolution rotary encoder. A table summarizing the major components of the stand is provided in Table A-1.

Table A-1. Test Stand Components

Component	Description	Supplier
Circulation Heater	4.5kW, CFMNA25J10S	Watlow
Injected Fuel HX	5” Diameter, 24” Length, Stainless Steel shell and tube, 4-pass, Narrow Baffles	ITT Standard
Return Fuel and Oil System HX	3” Diameter, 14” Length, Stainless Steel shell and tube	ITT Standard
Injected/Inlet Fuel HX	3” Diameter, 14” Length, Stainless Steel shell and tube	ITT Standard
Drive System Bearings	VPS-300 Pillow Block Bearing	Browning
Pump Coupling	PN 6A52: Clamp Style 2” Bore w/ Keyway x Blank Set Screw A-hub	Zero-Max
Motor	25HP, 460VAC, 40AMPS, NEMA 1,	Toshiba
VFD	30HP, 460VAC, 40AMPS, NEMA 1, PN VT130H9U4330	Toshiba
Rotary Encoder	XH25D-SS-3600-ABZC-28V/V-SM18	BEI Industrial

APPENDIX B

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Ford 6.7L Fuel System

Test Fuel: Ultra Low Sulfur Diesel

Test Number: ULSD-AF7947-60°C-FRD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Ford 6.7L Fuel System

Test Fuel: Ultra Low Sulfur Diesel
Test Number: ULSD-AF7947-60°C-FRD
Start of Test Date: July 22, 2011
End of Test Date: August 25, 2011
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) conducted a project with the US Army TARDEC on synthetic and alternative fuels. The project goal was to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI) DCI-4A at a rate of 9ppm, and a 1:1 blend of Jet A and the synthetic fuel with the CI/LI at rates of 9 ppm and 22.5 ppm. The desire was to perform eight 400 hour durability tests with duty cycles similar to a NATO cycle engine test. Five tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and two at 80°C (176 °F), for a total of seven tests. An eighth test was conducted to isolate fuel impact on two critical components. The lower temperature ULSD test was considered a baseline for comparison of other tests.

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Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Ford 6.7L system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Ford supplied engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The pump consisted of two high strength rods which compressed fuel to reach the desired rail pressure. Fuel then flowed to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled to a consistent temperature, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Figure B–1..

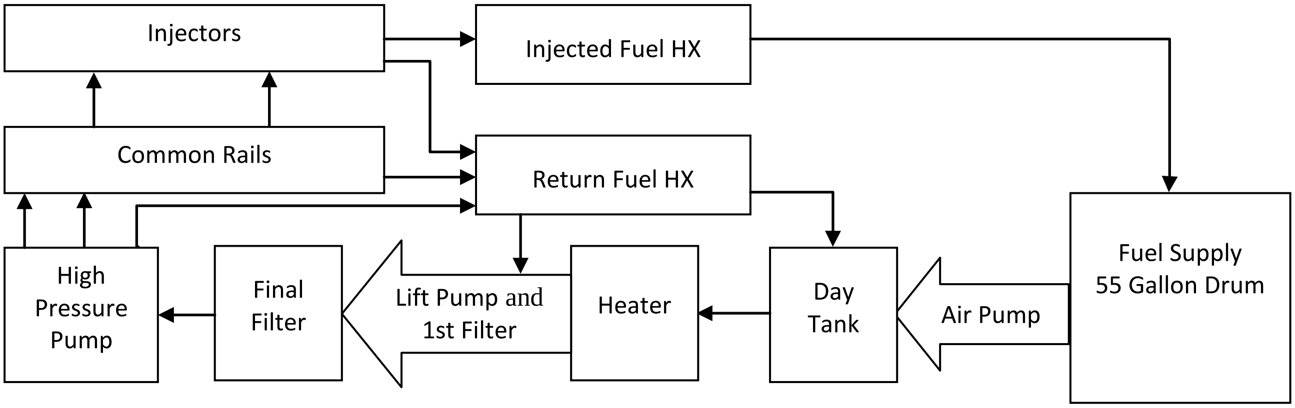

Figure B-1. Ford 6.7L Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10 hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table B–1.

Table B-1. NATO Cycle for Ford 6.7L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	600	0	0.5
2	2800	100	2
3	2940	0	0.5
4	2100	100	1
5*	600 to 2800	0 to 100	2
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2
10	1680	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Ford supplied ECM for monitoring purposes. Rail pressures were confirmed using the Ford service tool at various times throughout testing. The system did not experience any performance issues related to rail pressure during the course of the test, Figure B-2.

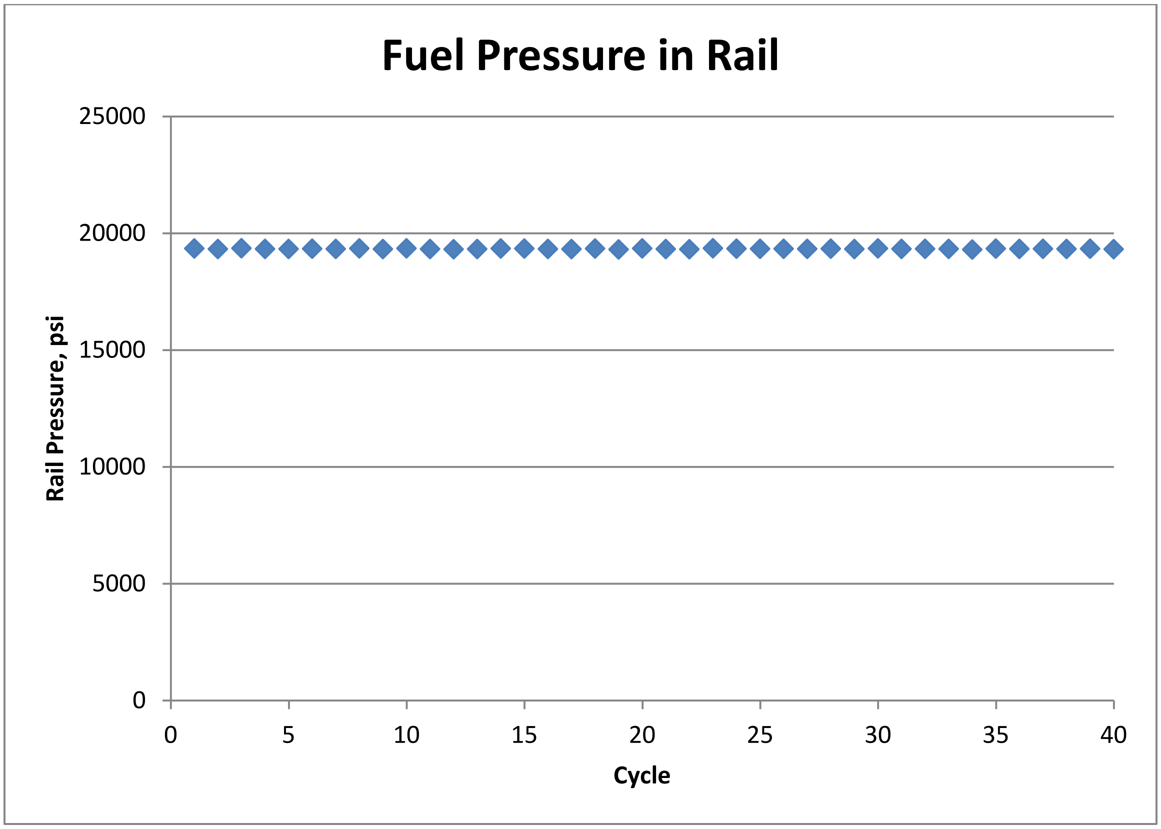

Figure B-2. Fuel Rail Pressure

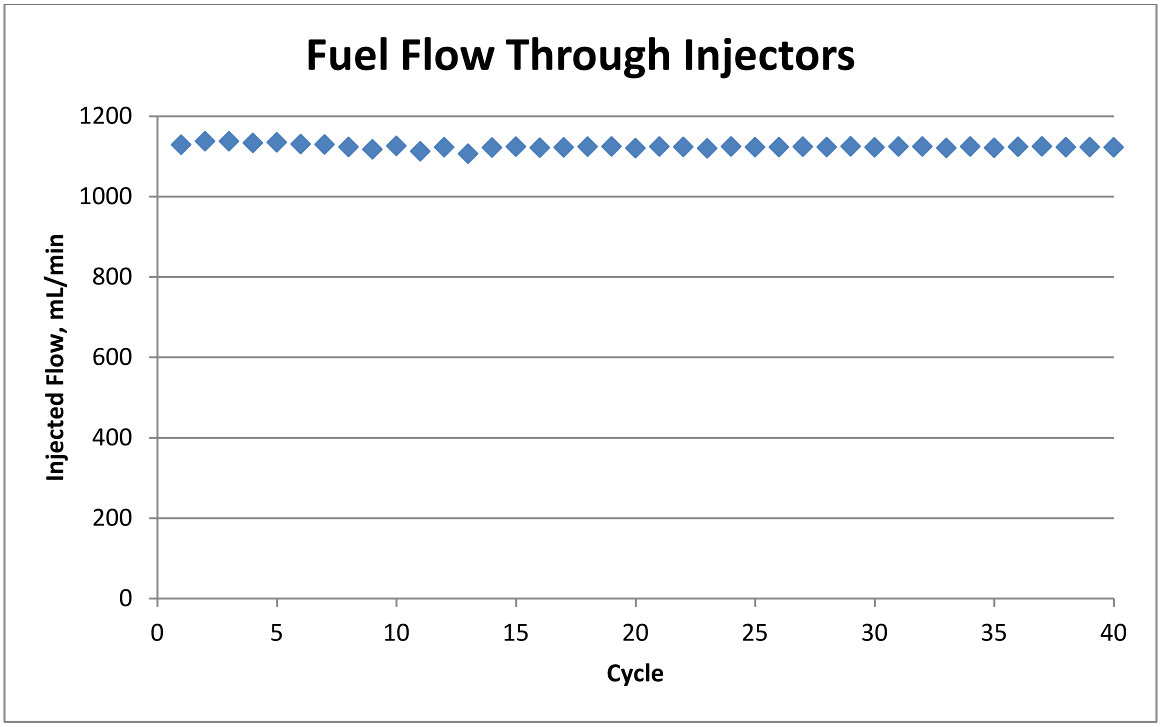

Figure B-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump volume control valve, rail protection check valve, and injector bypass/cooling flow.

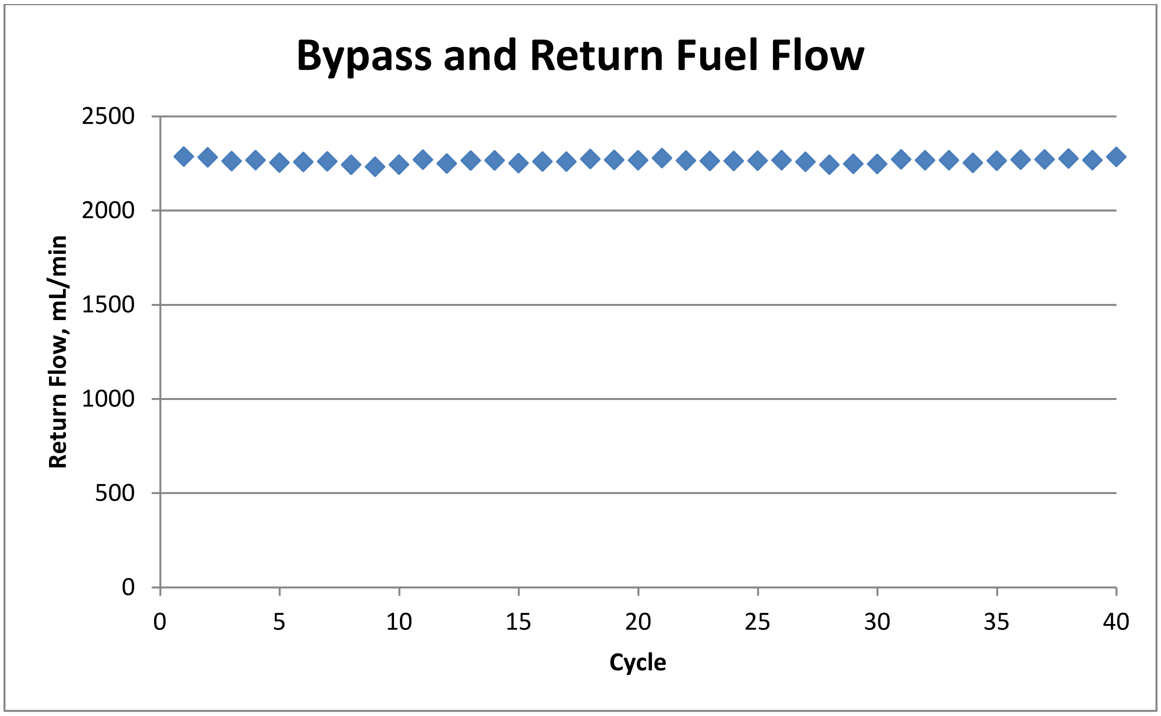

Figure B-4. Return Fuel Flow

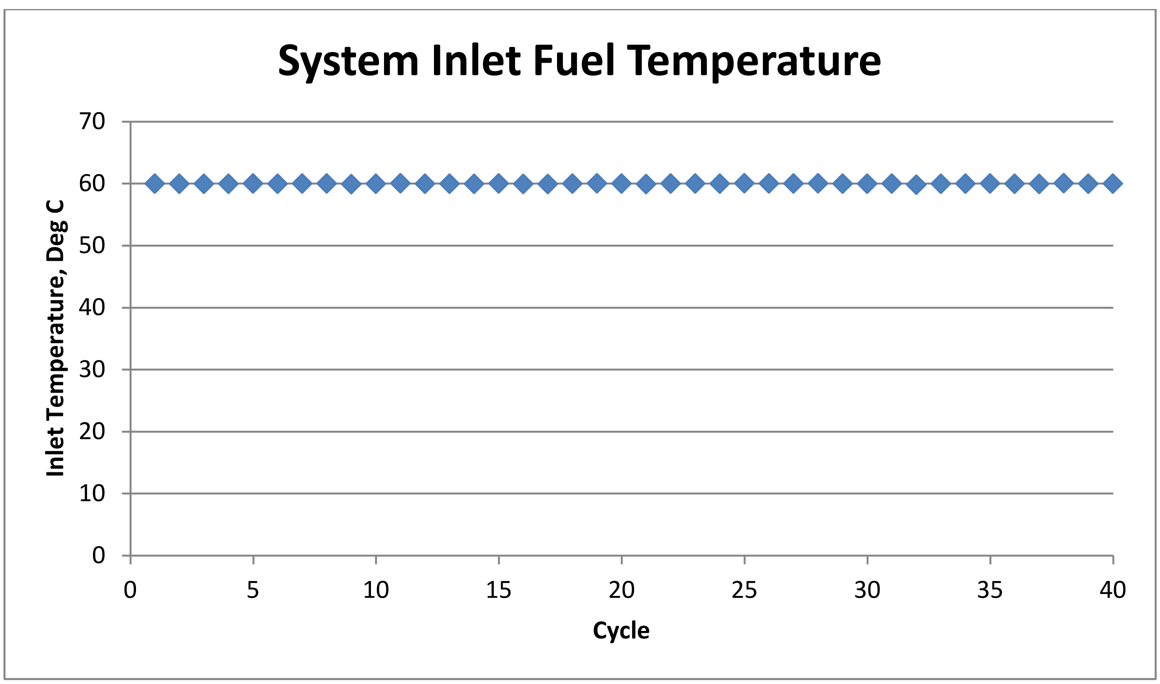

Figure B-5. System Inlet Fuel Temperature

Fuel filter inlet pressure is a measure of the pressure being developed by the lift pump and fuel/water separator unit of the system.

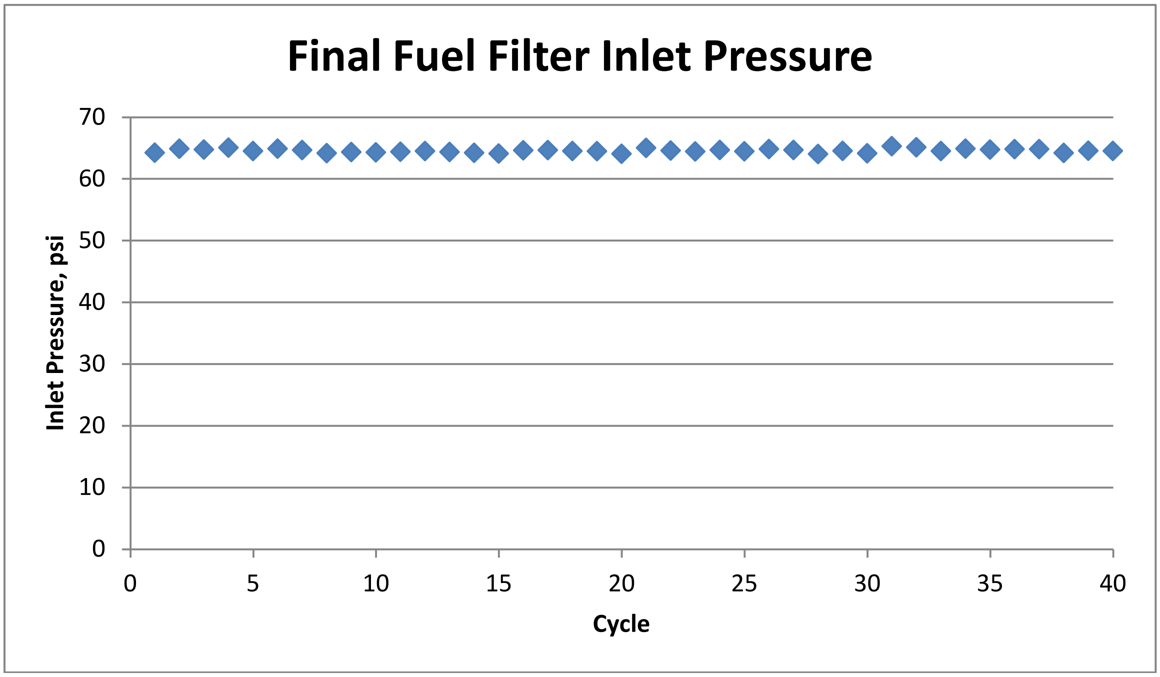

Figure B-6. Fuel Filter Pressure

Table B-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.4	58.0	61.4
Bypass Fuel Temperature, deg C	144.4	1.2	133.0	147.1
Rail Pressure, psi	19341.8	139.1	19014.2	19653.4
Injected Flow Rate, mL/min	1130.4	10.3	1092.4	1169.5
Return Fuel Flow Rate, mL/min	2259.2	18.9	2201.9	2313.1
Fuel Filter Inlet Pressure, psi	64.6	0.3	63.7	65.3
Test Hours 100-200				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.4	58.6	61.5
Bypass Fuel Temperature, deg C	144.7	1.3	133.8	147.6
Rail Pressure, psi	19333.9	134.9	19025.2	19638.7
Injected Flow Rate, mL/min	1120.6	10.8	1075.7	1161.5
Return Fuel Flow Rate, mL/min	2263.2	10.6	2225.6	2293.8
Fuel Filter Inlet Pressure, psi	64.4	0.3	63.6	65.1
Test Hours 200-300				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.4	58.1	61.8
Bypass Fuel Temperature, deg C	144.0	1.4	124.8	146.3
Rail Pressure, psi	19337.6	139.1	19021.5	19660.8
Injected Flow Rate, mL/min	1123.7	8.2	1027.1	1157.5
Return Fuel Flow Rate, mL/min	2260.1	13.3	2220.5	2295.3
Fuel Filter Inlet Pressure, psi	64.5	0.3	63.7	65.5
Test Hours 300-400				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.5	48.8	61.9
Bypass Fuel Temperature, deg C	143.2	1.8	120.9	146.2
Rail Pressure, psi	19332.9	134.4	19006.8	19679.1
Injected Flow Rate, mL/min	1123.7	5.8	1106.3	1153.1
Return Fuel Flow Rate, mL/min	2269.3	12.6	2190.2	2304.8
Fuel Filter Inlet Pressure, psi	64.8	0.4	63.8	65.8

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figure B-7 and B-8. It should be noted that the final values for 100 and 200 hour BOCLE tests, and 100 and 400 hour HFRR were the same.

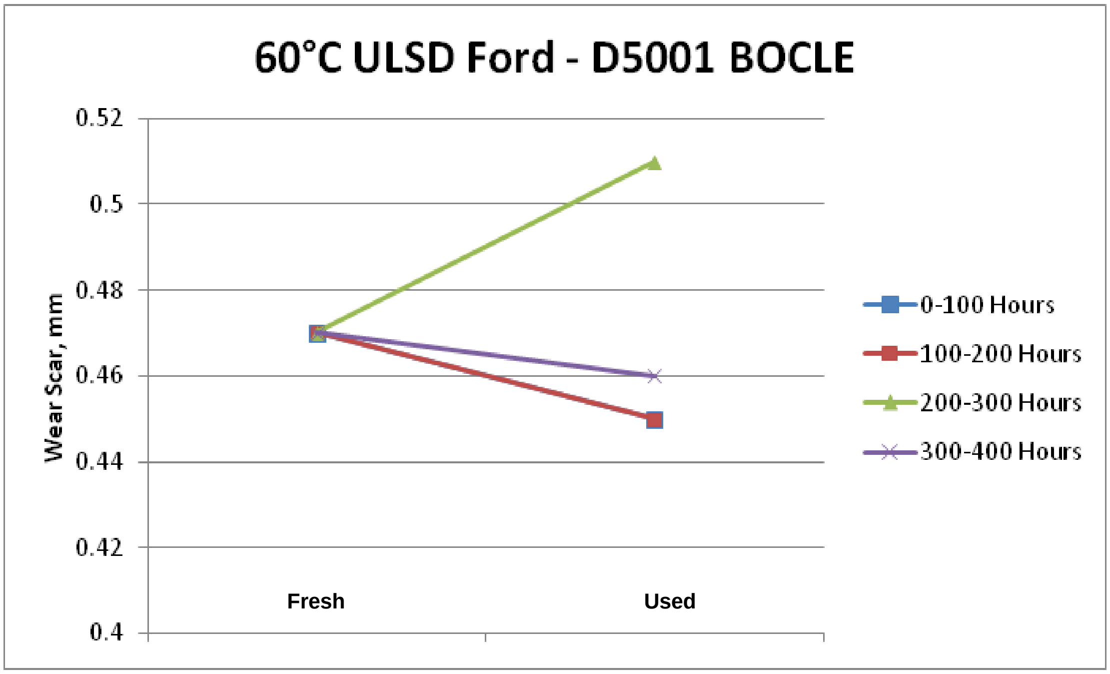

Figure B-7. ASTM D5001 BOCLE

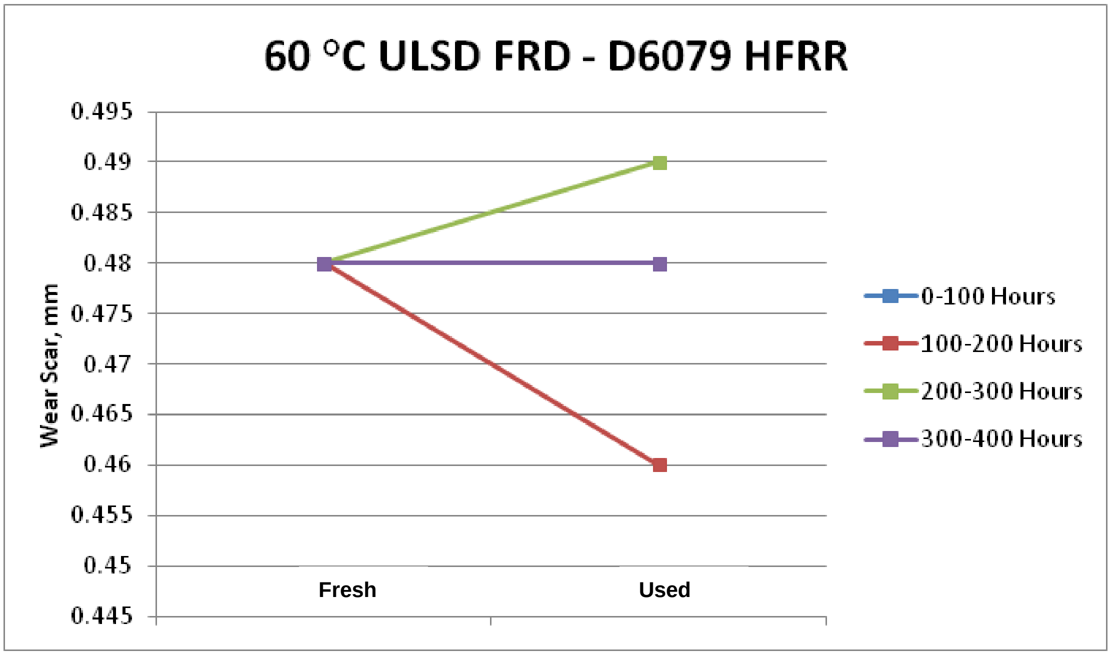

Figure B-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on ULSD at 60°C inlet temperature.

Fuel Pump

Figure B-9. Front Pump Bushing

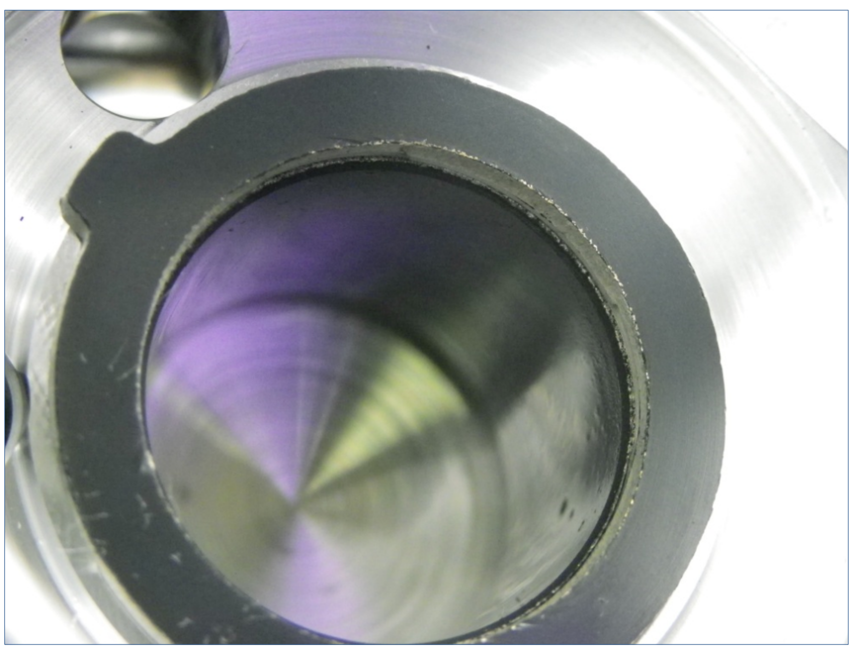

Figure B-10. Rear Pump Bushing

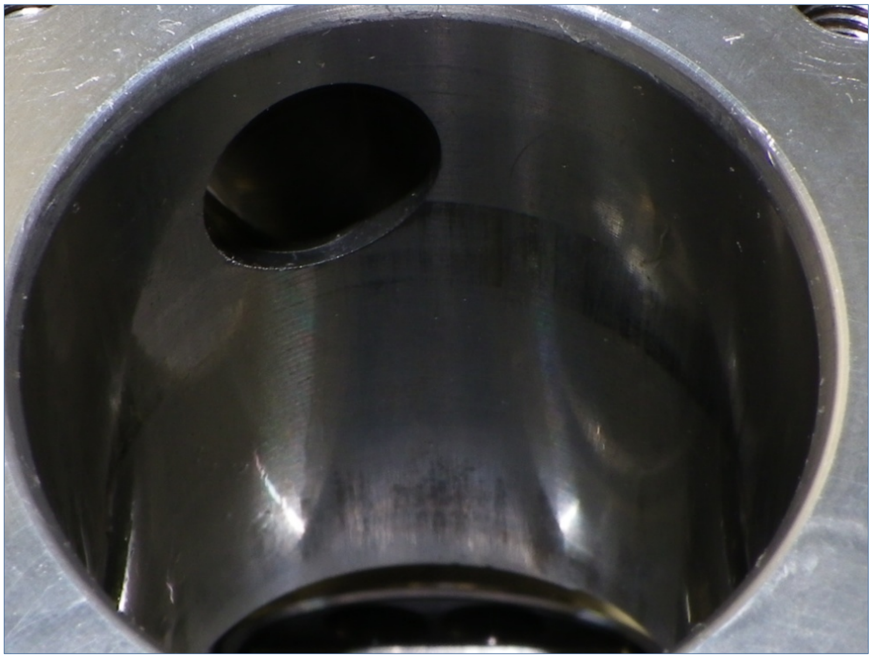

Figure B-11. Left Pump Bore Side 1

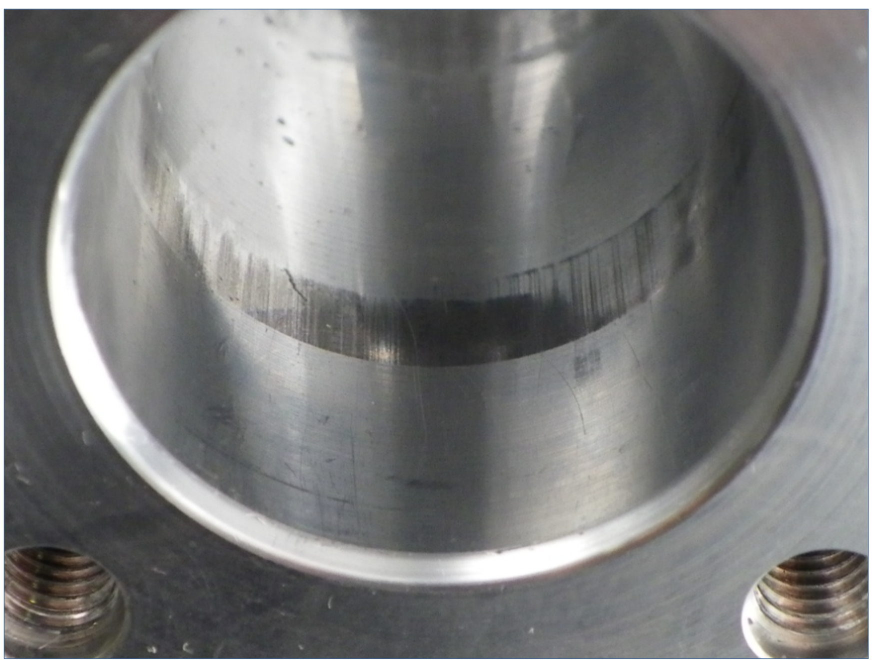

Figure B-12. Left Pump Bored Side 2

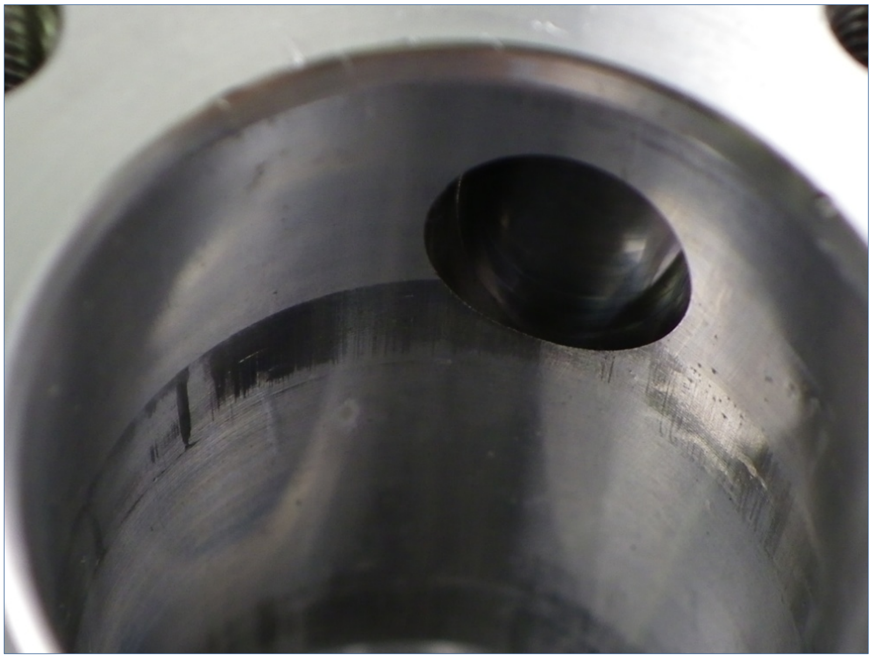

Figure B-13. Right Pump Bore Side 1

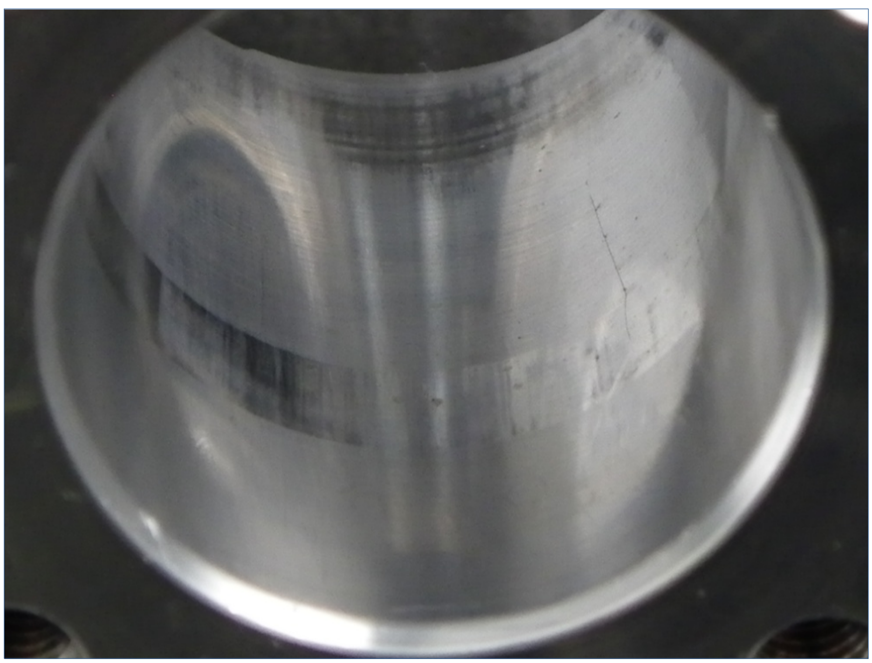

Figure B-14. Right Pump Bore Side 2

Figure B-15. Left Pump Cam Follower 1

Figure B-16. Left Pump Cam Follower Side 2

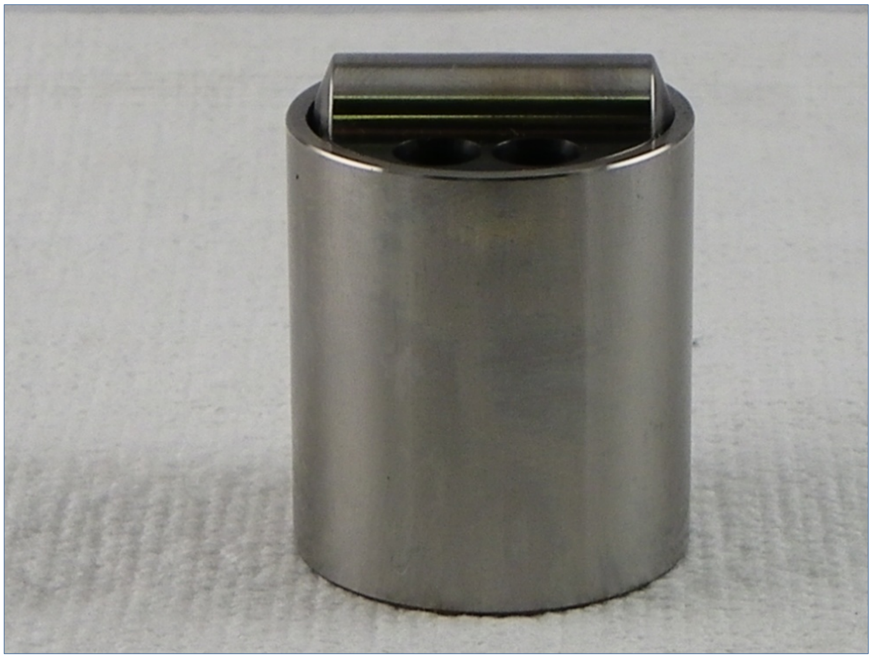

Figure B-17. Right Cam Follower Side 1

Figure B-18. Right Cam Follower Side 2

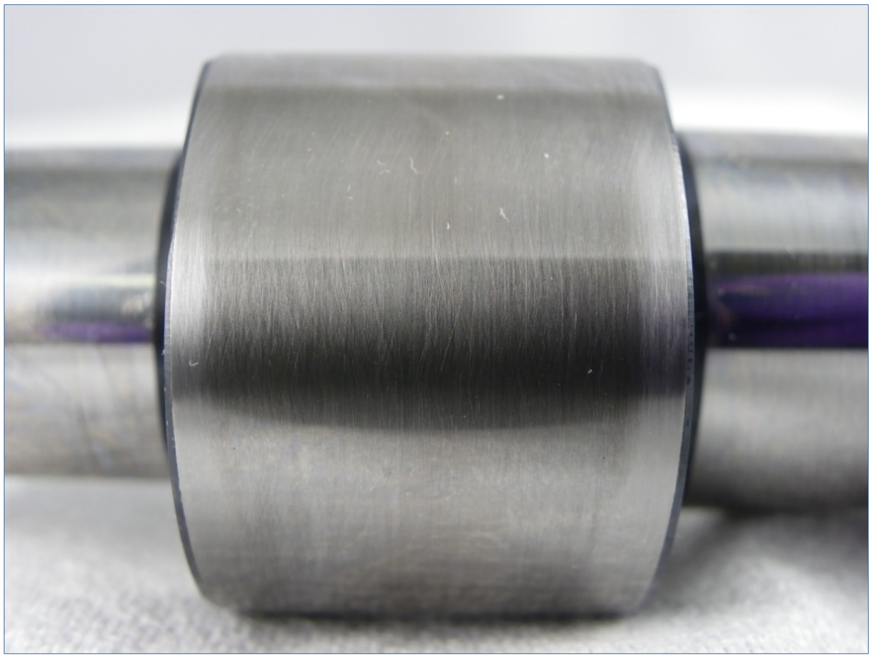

Figure B-19. Camshaft Lobe

Fuel Injector

Figure B-20. Injector Needle

Figure B-21. Upper Hydraulic Coupler Piston End

Figure B-22. Upper Hydraulic Coupler Piston Profile

Figure B-23. Lower Hydraulic Coupler Piston End

Figure B-24. Lower Hydraulic Coupler Piston Profile

Figure B-25. Intermediate Plate (Top)

Figure B-26. Intermediate Plate (Bottom)

Figure B-27. Control Valve Plate (Top)

Figure B-28. Control Valve Plate (Bottom)

Figure B-29. Fuel Injector Control Valve

APPENDIX C

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Ford 6.7L Fuel System

Test Fuel: FT SPK with 9 ppm DCI-4A

Test Number: SPK-AF868-60°C-FRD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Ford 6.7L Fuel System

Test Fuel: FT SPK with 9 ppm DCI-4A

Test Number: SPK-AF868-60°C-FRD

Start of Test Date: October 6, 2011

End of Test Date: October 31, 2011

Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC

Force Projection Technologies

Warren, Michigan

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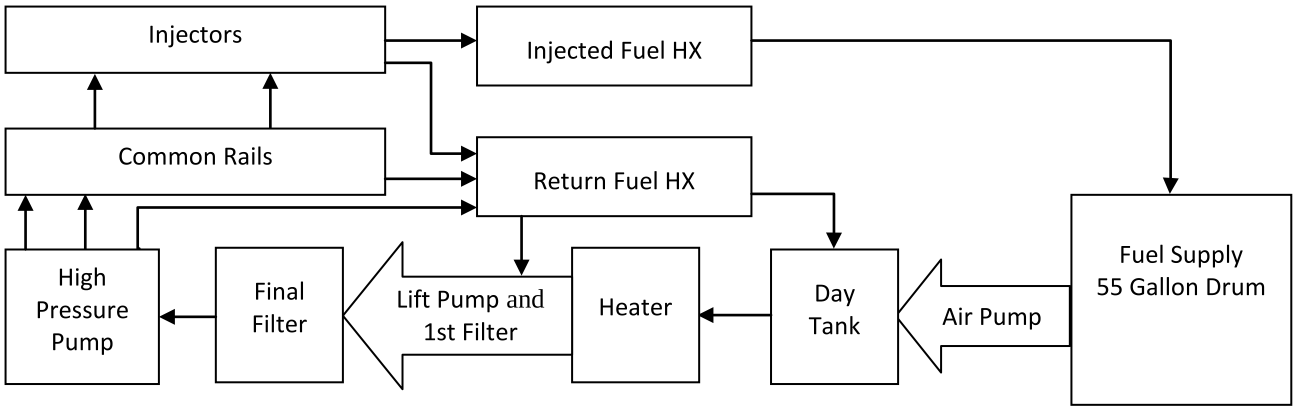

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Test Cycle

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*Step 5 cycles between idle and rated conditions

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The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Ford supplied ECM for monitoring purposes. Rail pressures were confirmed using the Ford service tool at various times throughout testing. The system did not experience any performance issues related to rail pressure during the course of the test, Figure C-2.

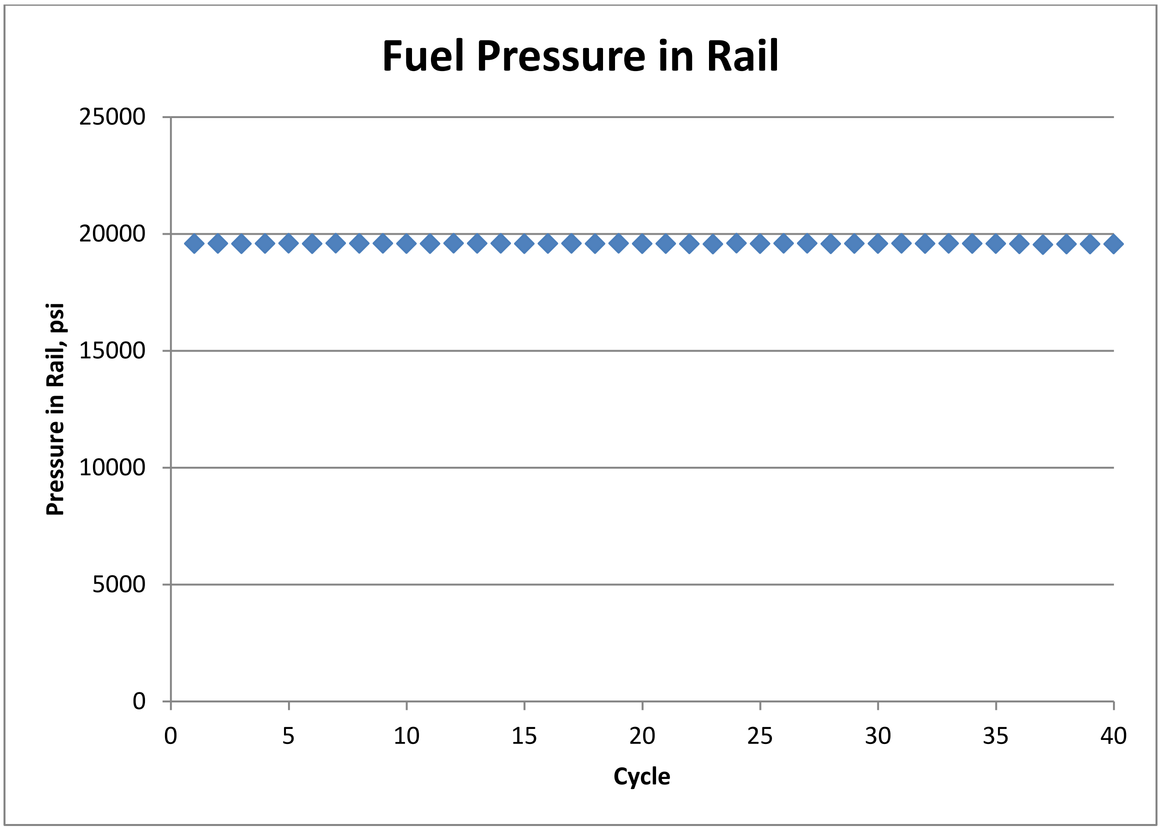

Figure C-2. Fuel Rail Pressure

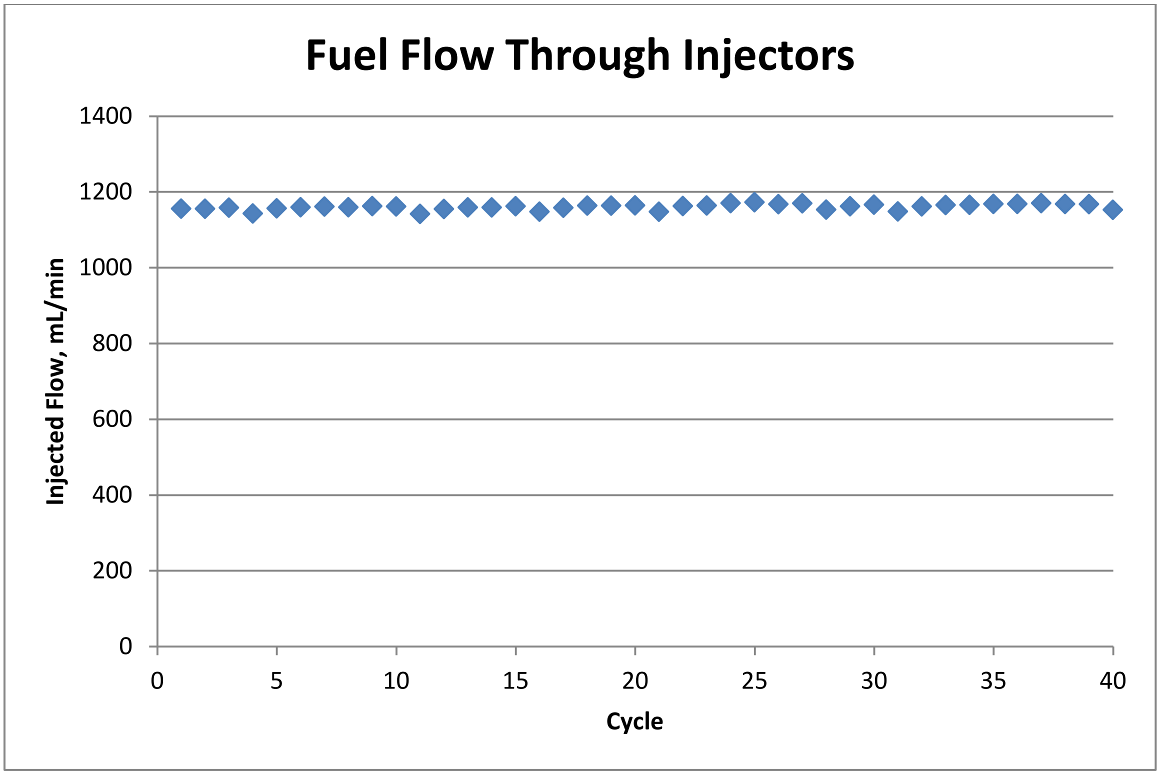

Figure C-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump volume control valve, rail protection check valve, and injector bypass/cooling flow.

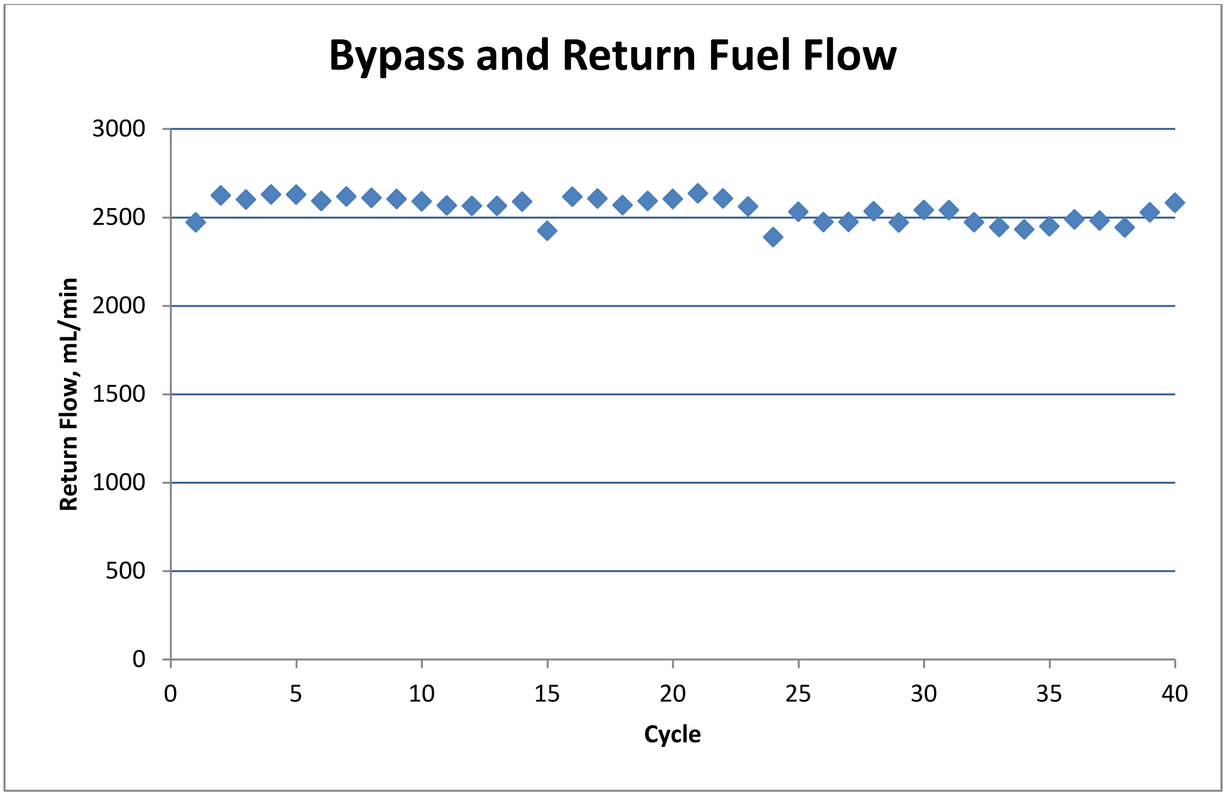

Figure C-4. Return Fuel Flow

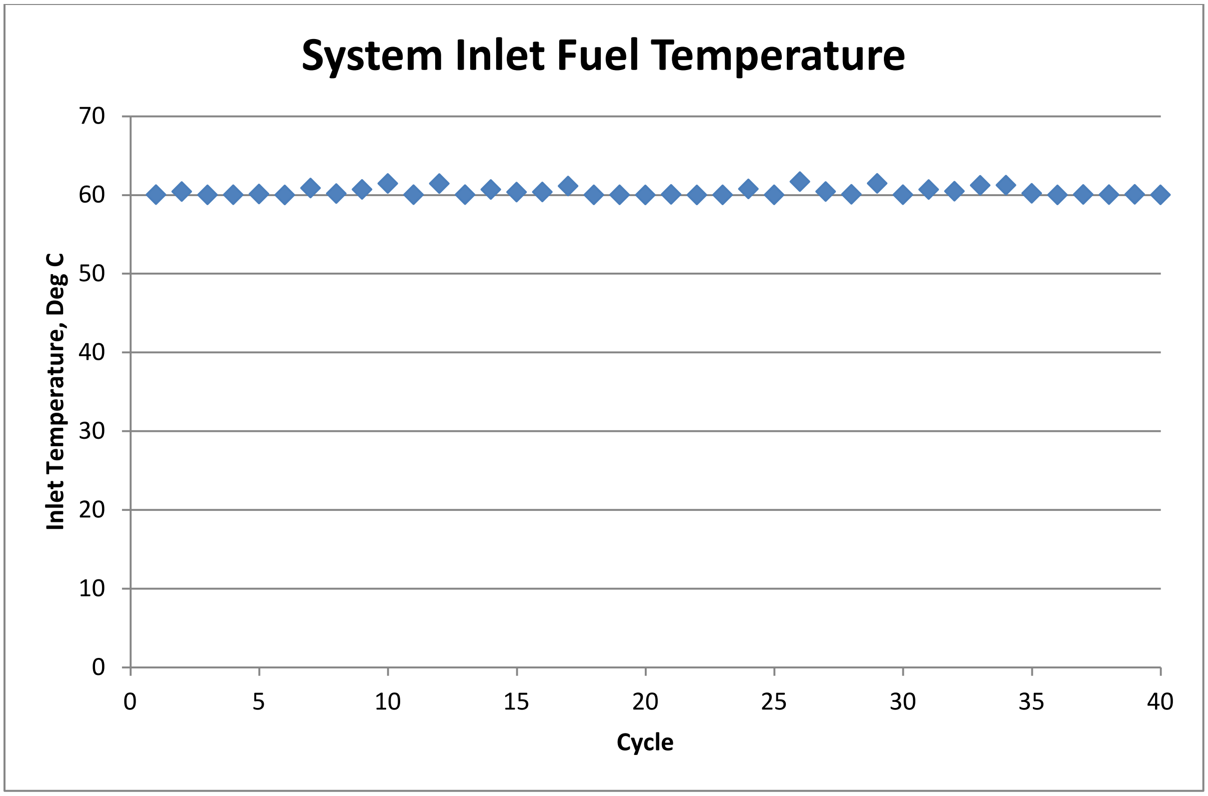

Figure C-5. System Inlet Fuel Temperature

Fuel filter inlet pressure is a measure of the pressure being developed by the lift pump and fuel/water separator unit of the system.

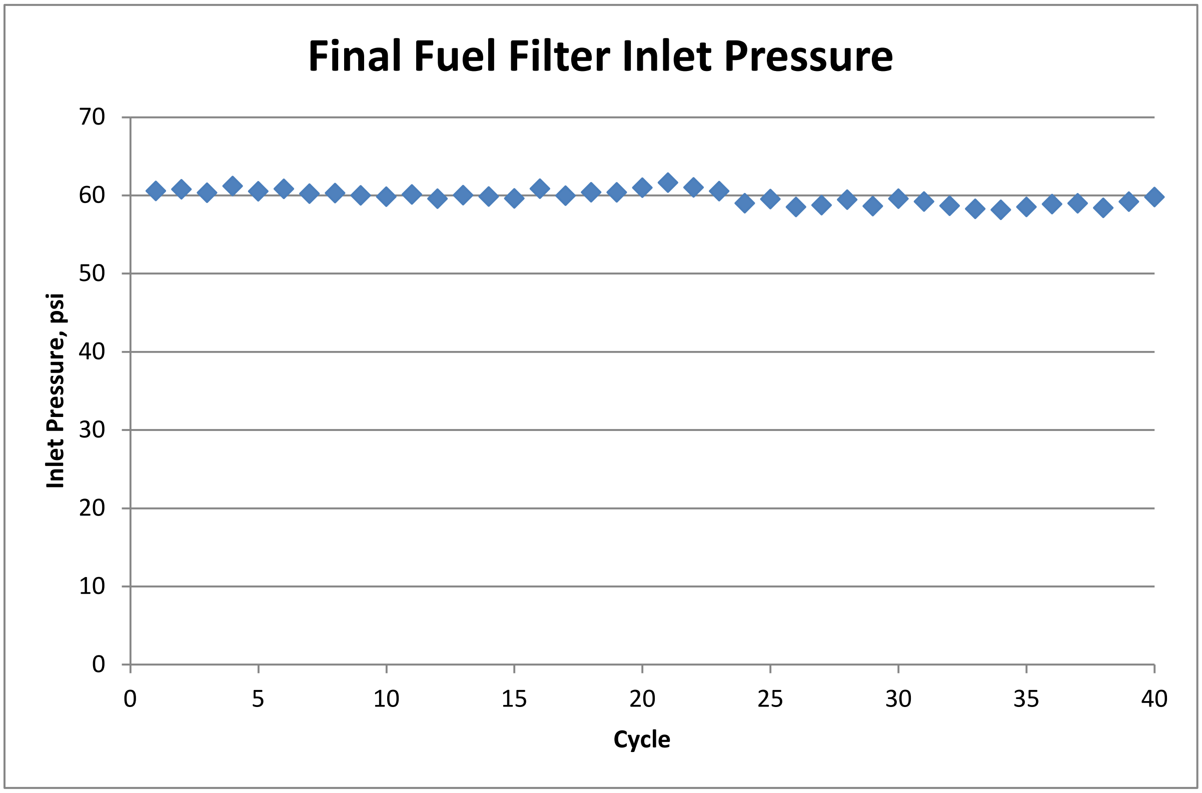

Figure C-6. Fuel Filter Pressure

Table C-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.4	0.6	59.1	62.7
Bypass Fuel Temperature, deg C	65.9	0.9	60.3	68.3
Rail Pressure, psi	19593	43	19462	19753
Injected Flow Rate, mL/min	1158.9	16.6	1115.8	1255.3
Return Fuel Flow Rate, mL/min	2596.9	45.4	2381.1	2652.6
Fuel Filter Inlet Pressure, psi	60.5	0.4	59.4	61.9
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.4	0.7	58.8	62.8
Bypass Fuel Temperature, deg C	65.2	1.2	59.8	68.4
Rail Pressure, psi	19593	44	19396	19749
Injected Flow Rate, mL/min	1159.1	19.2	1109.9	1251.7
Return Fuel Flow Rate, mL/min	2569.8	54.6	2405.4	2668.4
Fuel Filter Inlet Pressure, psi	60.2	0.5	58.6	62.1
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.5	0.8	59.0	63.0
Bypass Fuel Temperature, deg C	64.8	1.2	59.6	67.9
Rail Pressure, psi	19588	43	19444	19701
Injected Flow Rate, mL/min	1165.2	20.2	1106.5	1261.2
Return Fuel Flow Rate, mL/min	2521.9	70.7	2361.3	2655.3
Fuel Filter Inlet Pressure, psi	59.7	1.0	58.1	62.0
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.4	0.7	59.0	63.1
Bypass Fuel Temperature, deg C	64.8	1.1	59.2	67.8
Rail Pressure, psi	19579	44	19433	19745
Injected Flow Rate, mL/min	1165.3	19.0	1117.1	1260.3
Return Fuel Flow Rate, mL/min	2486.4	48.7	2408.9	2651.6
Fuel Filter Inlet Pressure, psi	58.8	0.5	57.9	60.5

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figure B-7 and B-8. It should be noted that the final values for 100 and 400 hour BOCLE tests were the same.

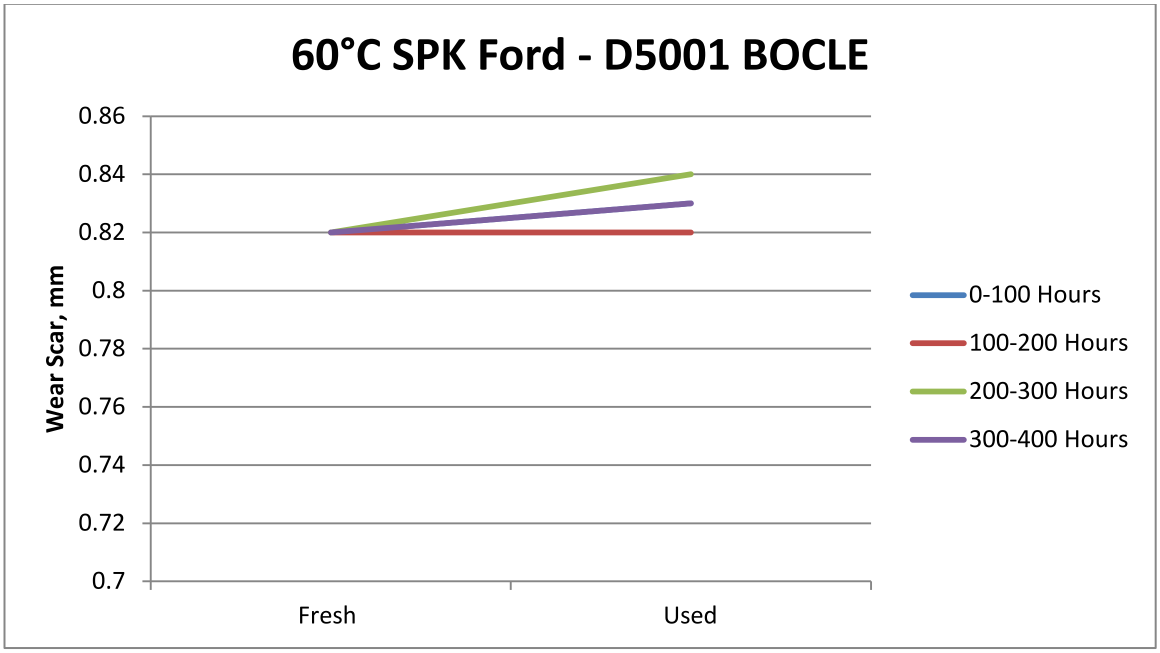

Figure C-7. ASTM D5001 BOCLE

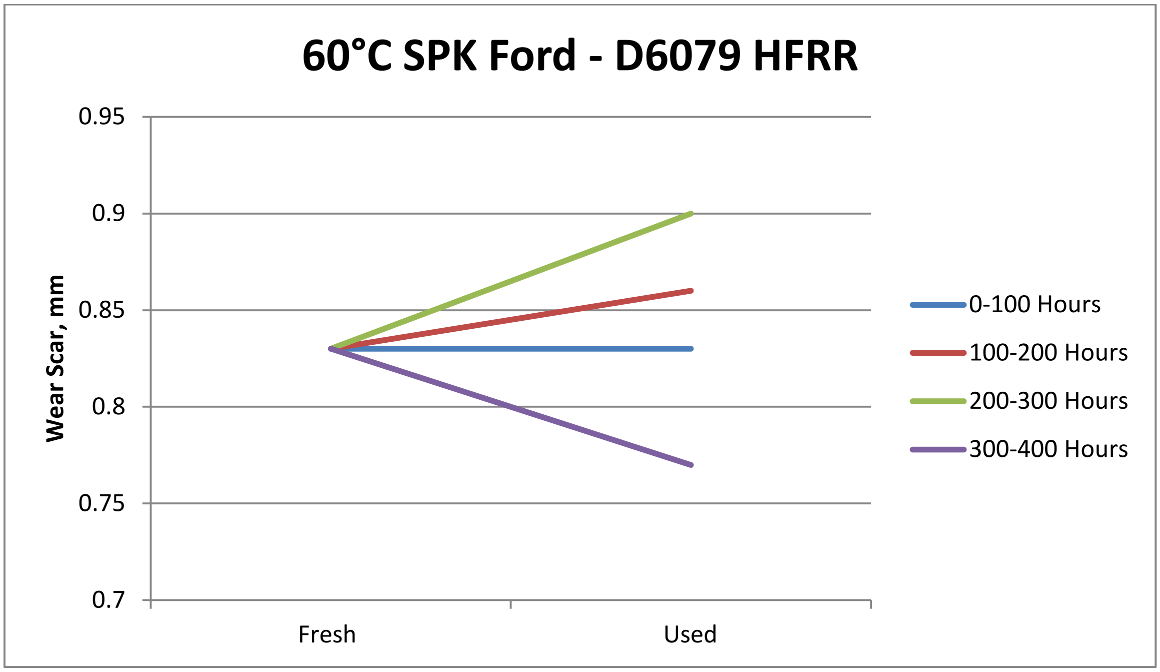

Figure C-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on SPK at 60°C inlet temperature.

Fuel Pump

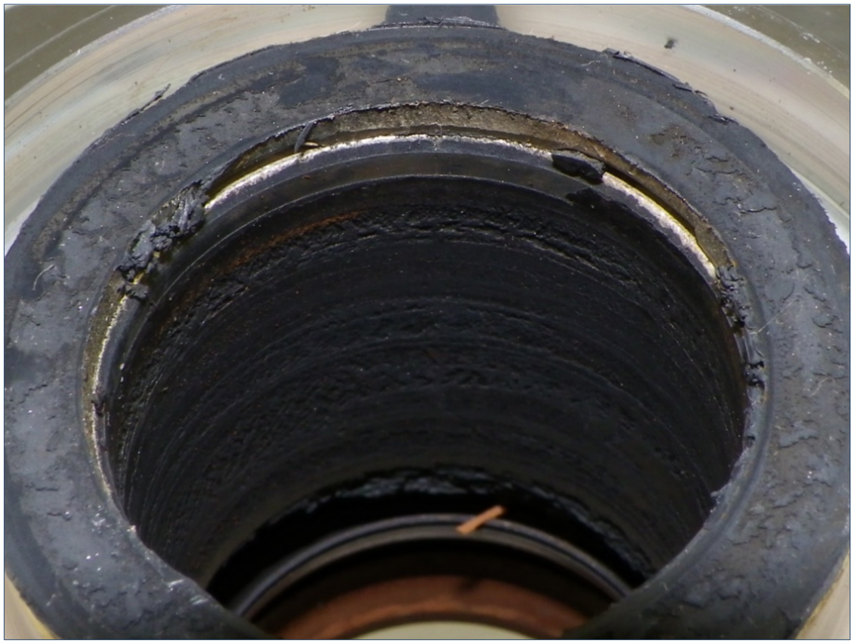

Figure C-9. Front Pump Bushing

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Figure C-10. Rear Pump Bushing

Figure C-11. Left Pump Bore Side 1

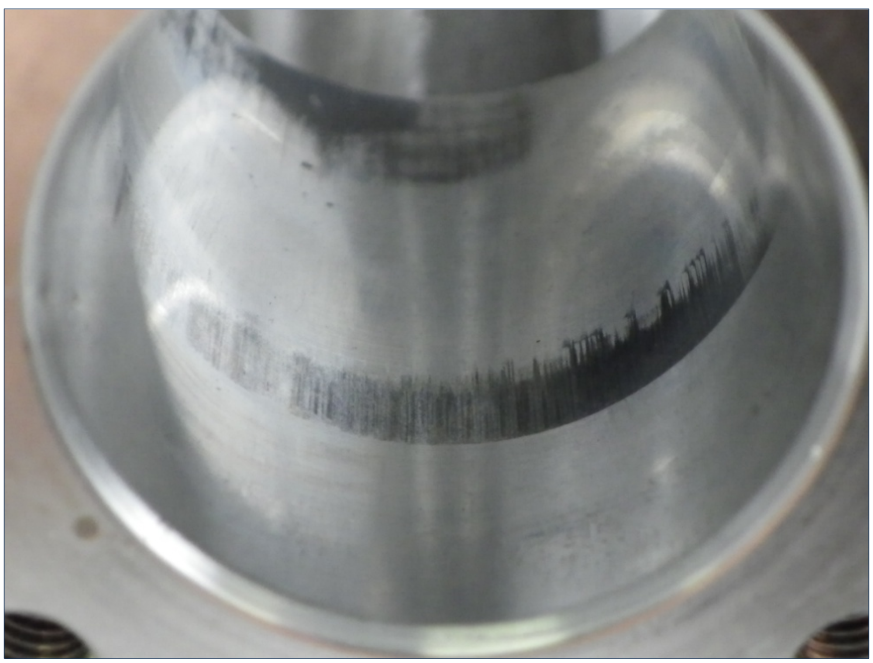

Figure C-12. Left Pump Bored Side 2

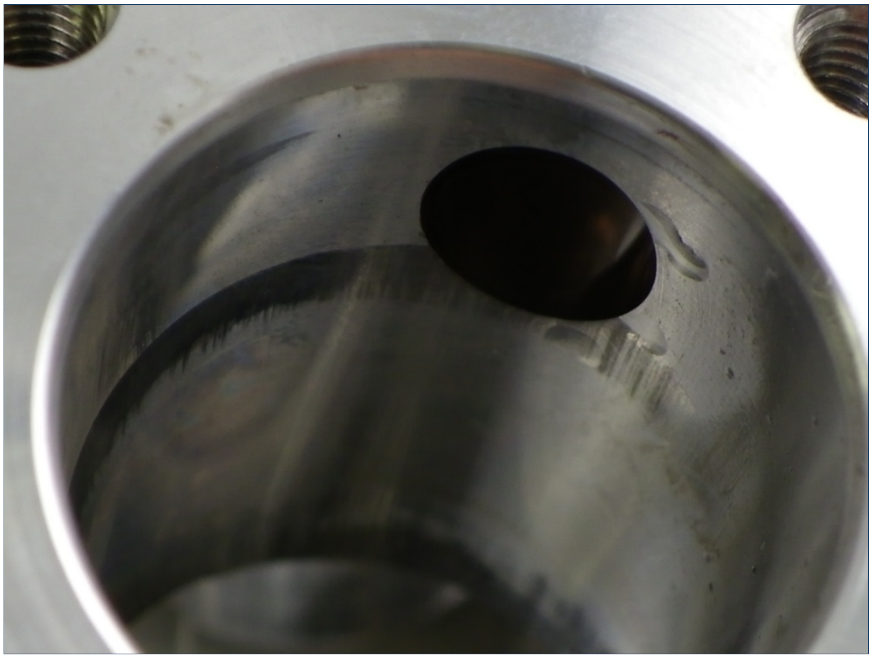

Figure C-13. Right Pump Bore Side 1

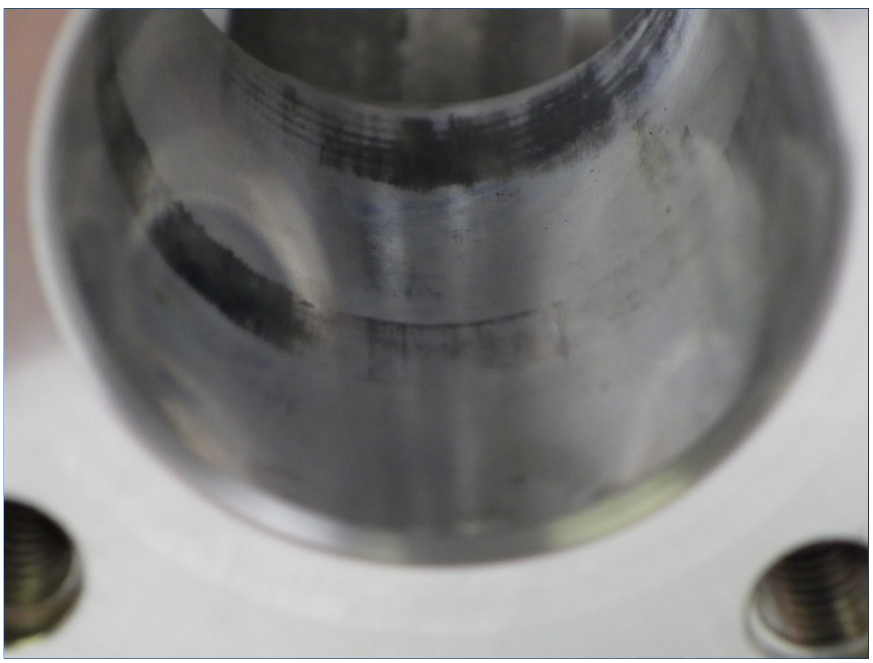

Figure C-14. Right Pump Bore Side 2

Figure C-15. Left Cam Follower Side 1

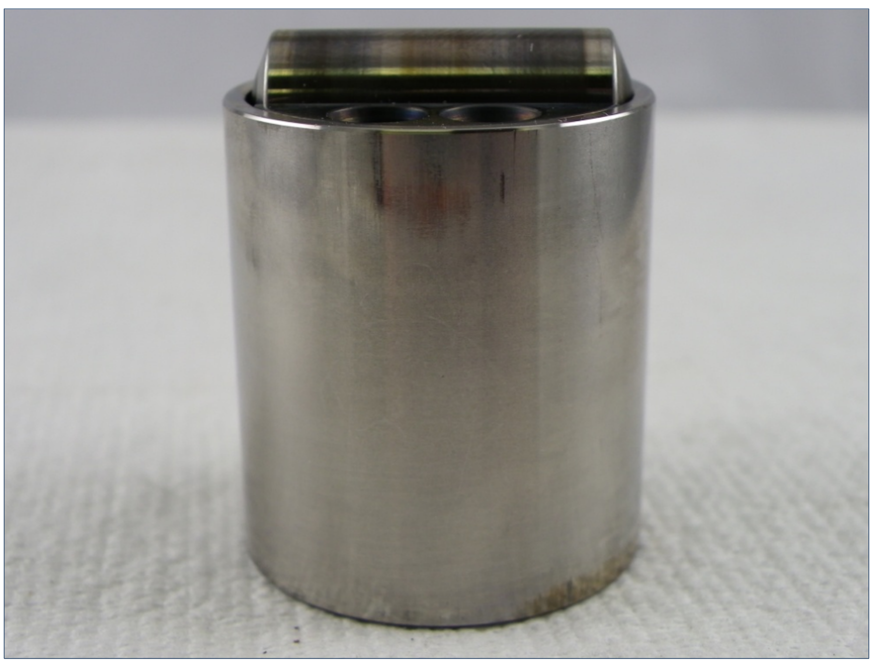

Figure C-16. Left Cam Follower Side 2

Figure C-17. Right Cam Follower Side 1

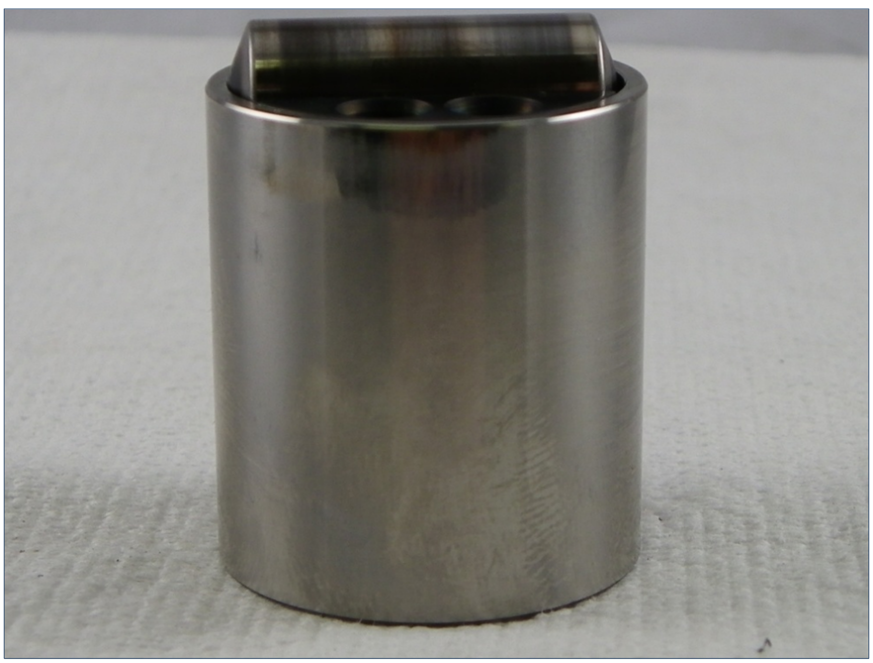

Figure C-18. Right Cam Follower Side 2

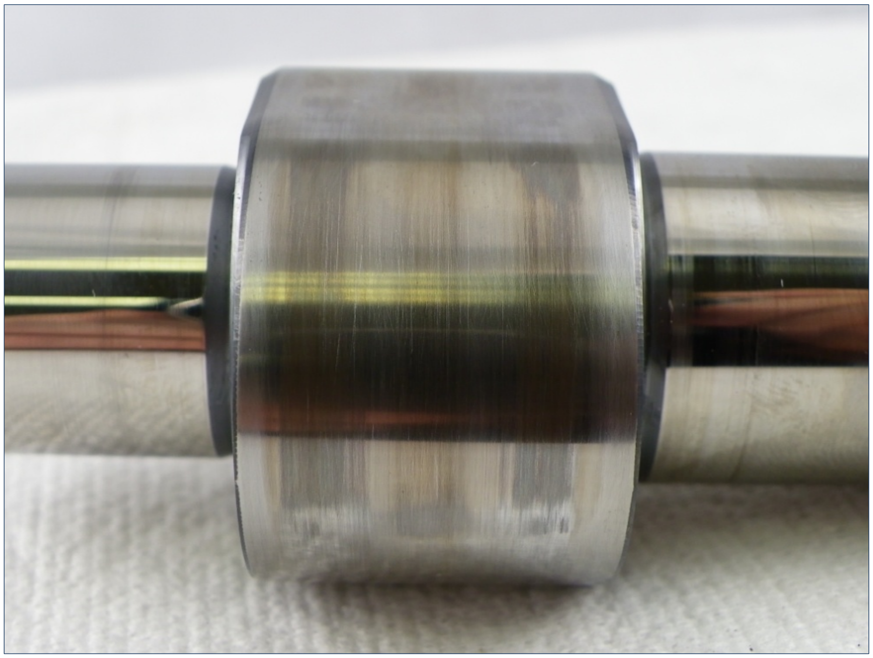

Figure C-19. Camshaft Lobe

Fuel Injector

Figure C-20. Injector Needle

Figure C-21. Upper Hydraulic Coupler Piston Side A

Figure C-22. Upper Hydraulic Coupler Piston Side B

Figure C-23. Lower Hydraulic Coupler Piston Side A

Figure C-24. Lower Hydraulic Coupler Piston Side B

Figure C-25. Intermediate Plate (Top)

Figure C-26. Intermediate Plate (Bottom)

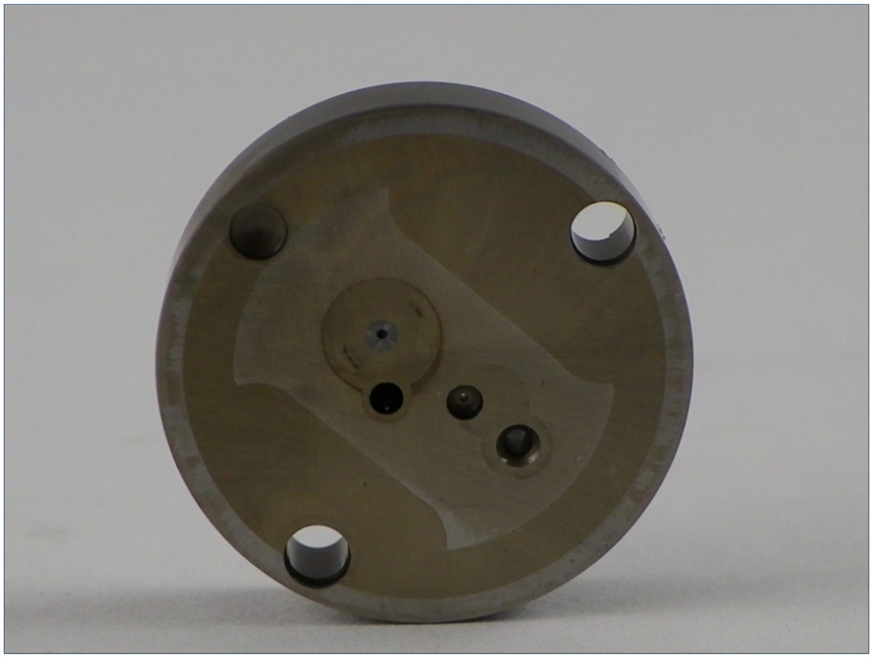

Figure C-27. Control Valve Plate (Top)

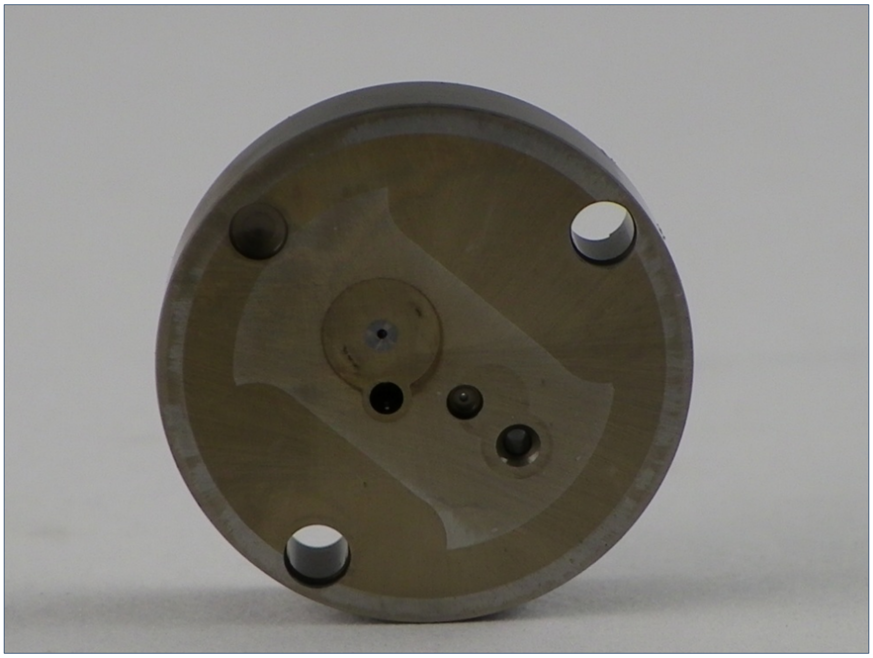

Figure C-28. Control Valve Plate (Bottom)

Figure C-29. Fuel Injector Control Valve

APPENDIX D

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Ford 6.7L Fuel System

FT SPK with 9ppm DCI-4A

SPK-AF868-80°C-FRD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Ford 6.7L Fuel System

Test Fuel: FT SPK with 9 ppm DCI-4A

Test Number: SPK-AF868-80°C-FRD

Start of Test Date: September 6, 2011

End of Test Date: October 3, 2011

Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC

Force Projection Technologies

Warren, Michigan

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) conducted a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal was to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI) DCI-4A at a rate of 9 ppm, and a 1:1 blend of Jet A and the synthetic fuel with the CI/LI at rates of 9 ppm and 22.5 ppm. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Five tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and two at 80°C (176 °F), for a total of seven tests. An eighth test was conducted to isolate fuel impact on two critical components. The lower temperature ULSD test was considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Ford 6.7L fuel system manufactured by Bosch. The fuel-lubricated high pressure pump allows the system to reach rail pressures of up to 20,000 psi. It is operated at the same rotational speed as the engine crankshaft for a rated condition of 2800 rpm. Within the pump, the camshaft drives two plungers, oriented in a "V" configuration, which pressurize the fuel entering the rail. Each plunger is driven by two lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure system consists of a lift pump and filter combination to remove large particles and water along with a high efficiency final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Ford 6.7L system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Ford supplied engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The pump consisted of two high strength rods which compressed fuel to reach the desired rail pressure. Fuel then flowed to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled to a consistent temperature, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Table D-1.

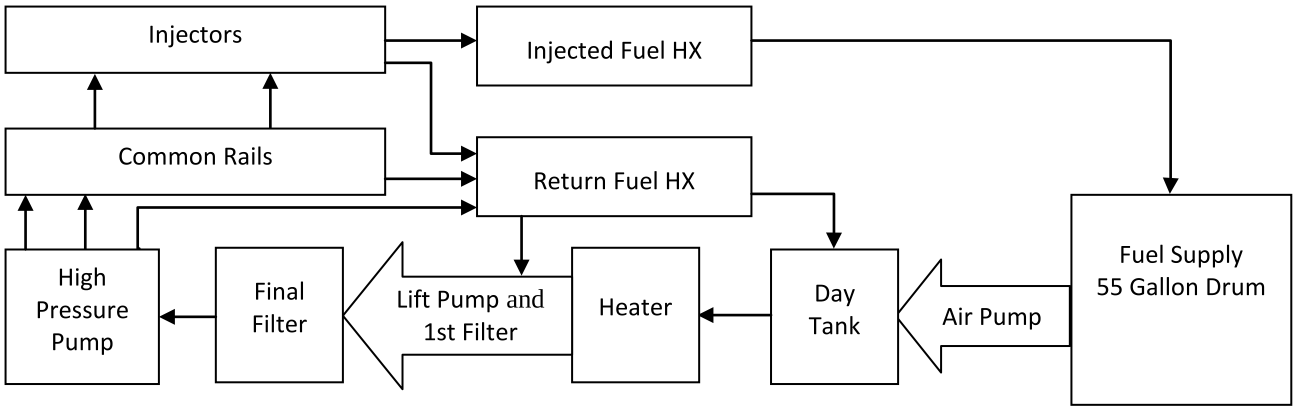

Figure D-1. Ford 6.7L Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table D-1.

Table D-1. NATO Cycle for Ford 6.7L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	600	0	0.5
2	2800	100	2
3	2940	0	0.5
4	2100	100	1
5*	600 to 2800	0 to 100	2
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2
10	1680	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Ford supplied ECM for monitoring purposes. Rail pressures were confirmed using the Ford service tool at various times throughout testing. The system did not experience any performance issues related to rail pressure during the course of the test, Figure D-2.

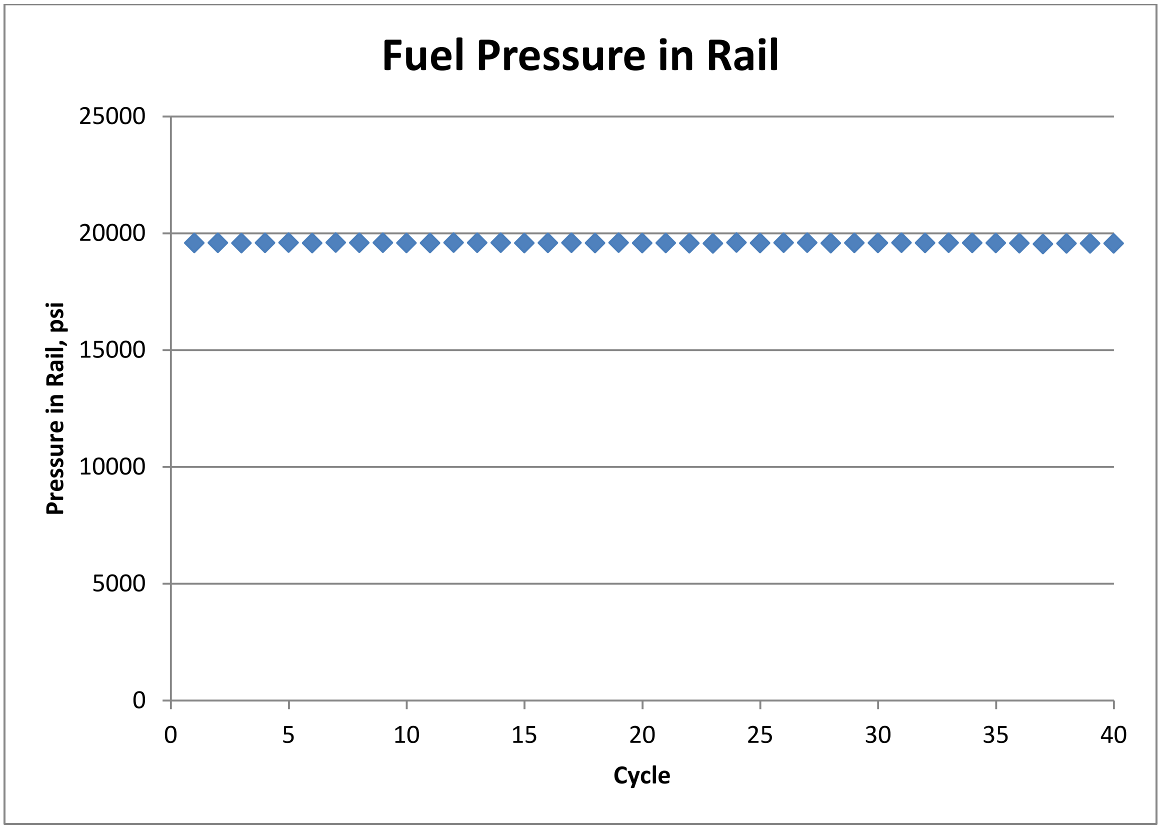

Figure D-2. Fuel Rail Pressure

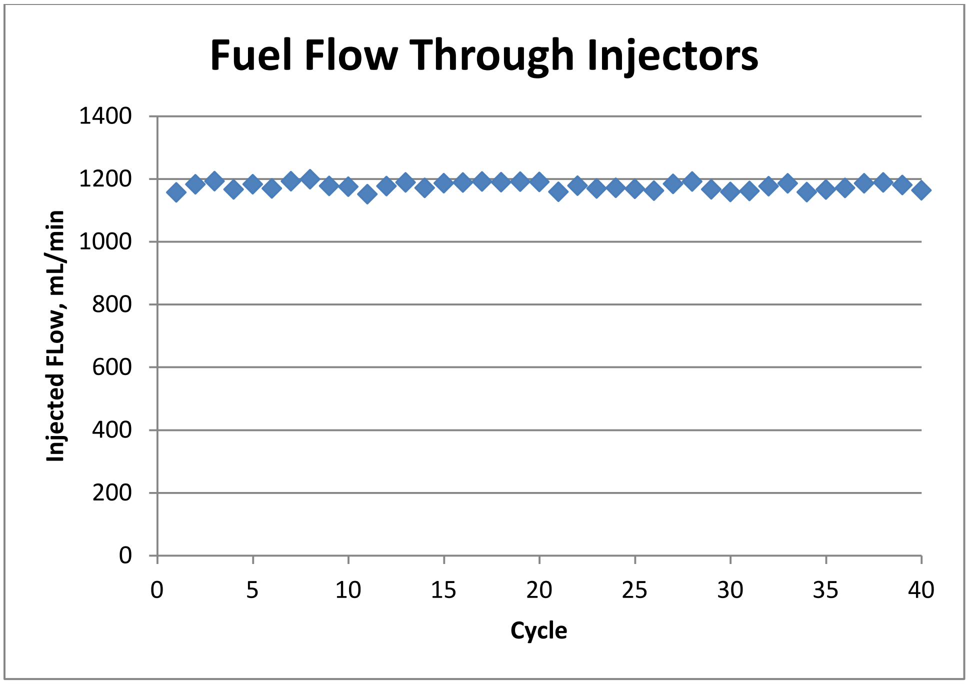

Figure D-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump volume control valve, rail protection check valve, and injector bypass/cooling flow. The bypass flow rate increased over the course of the test. This was likely due to degradation of the pump camshaft bushings, allowing for additional bypass fuel flow.

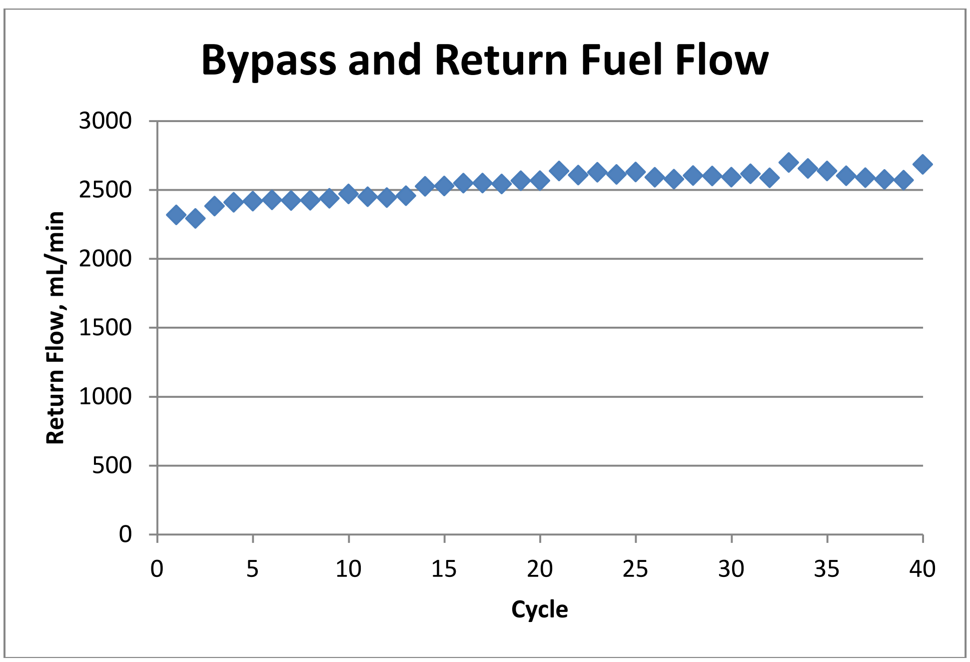

Figure D-4. Return Fuel Flow

Fuel filter inlet pressure is a measure of the pressure being developed by the lift pump and fuel/water separator unit of the system. As the bypass and return fuel flow rate increased, the developed pump pressure decreased.

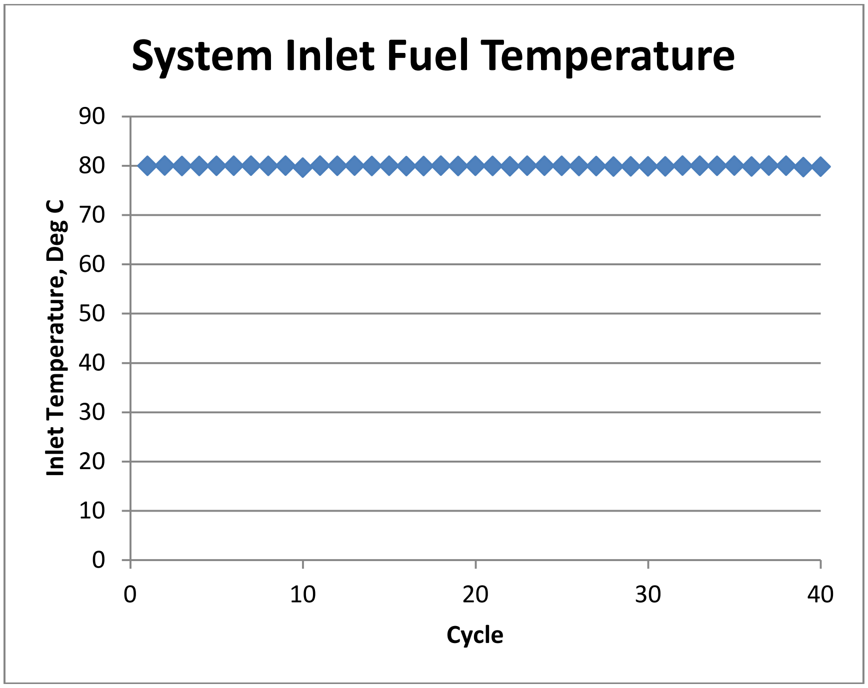

Figure D-5. System Inlet Fuel Temperature

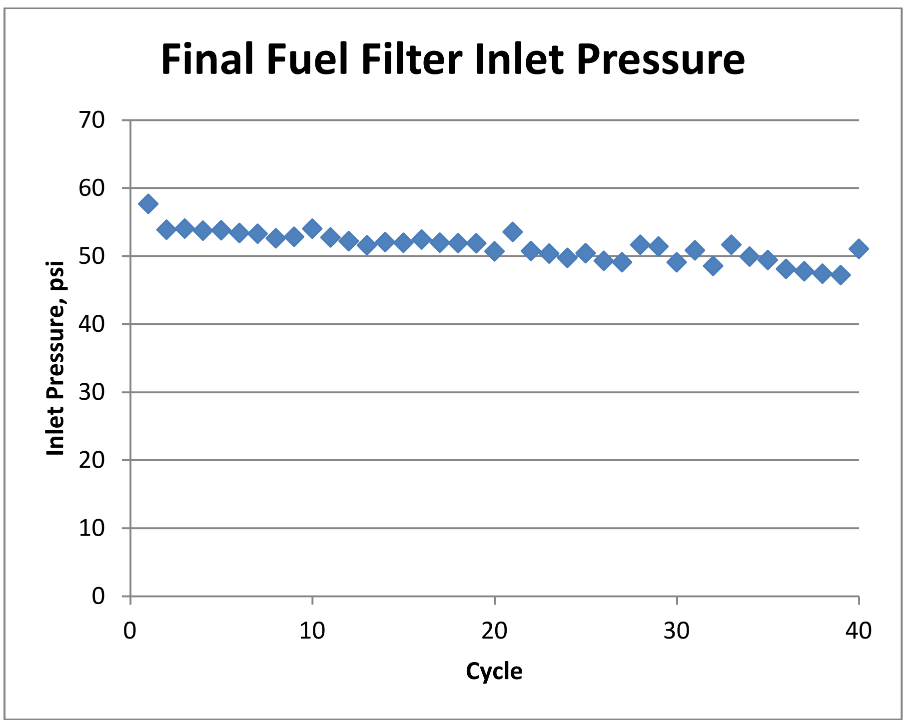

Figure D-6. Fuel Filter Pressure

Table D-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.9	1.2	68.9	82.8
Bypass Fuel Temperature, deg C	84.8	1.6	71.1	93.5
Rail Pressure, psi	19363	80	18897	19598
Injected Flow Rate, mL/min	1181.5	29.0	931.3	1310.9
Return Fuel Flow Rate, mL/min	2401.3	54.7	2253.6	2580.2
Fuel Filter Inlet Pressure, psi	54.0	1.4	51.9	58.8
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.9	1.0	70.1	81.8
Bypass Fuel Temperature, deg C	84.7	1.4	73.9	86.8
Rail Pressure, psi	19324	41	19183	19455
Injected Flow Rate, mL/min	1184.5	24.5	1095.5	1308.1
Return Fuel Flow Rate, mL/min	2518.5	47.6	2412.2	2590.2
Fuel Filter Inlet Pressure, psi	52.0	0.8	49.3	55.0
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.8	1.3	68.3	84.4
Bypass Fuel Temperature, deg C	83.4	1.7	70.3	85.8
Rail Pressure, psi	19322	53	18687	19455
Injected Flow Rate, mL/min	1172.9	29.0	894.7	1295.7
Return Fuel Flow Rate, mL/min	2608.4	22.6	2547.1	2705.5
Fuel Filter Inlet Pressure, psi	50.6	1.5	47.8	55.4
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.9	1.3	66.4	84.7
Bypass Fuel Temperature, deg C	83.8	1.5	58.8	85.9
Rail Pressure, psi	19320	59	18584	19451
Injected Flow Rate, mL/min	1175.4	34.6	796.6	1308.5
Return Fuel Flow Rate, mL/min	2622.0	46.2	2531.9	2753.7
Fuel Filter Inlet Pressure, psi	49.2	1.7	46.2	57.5

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figure D-7 and D-8. It should be noted that the final values for 200 and 300 hour BOCLE tests were the same.

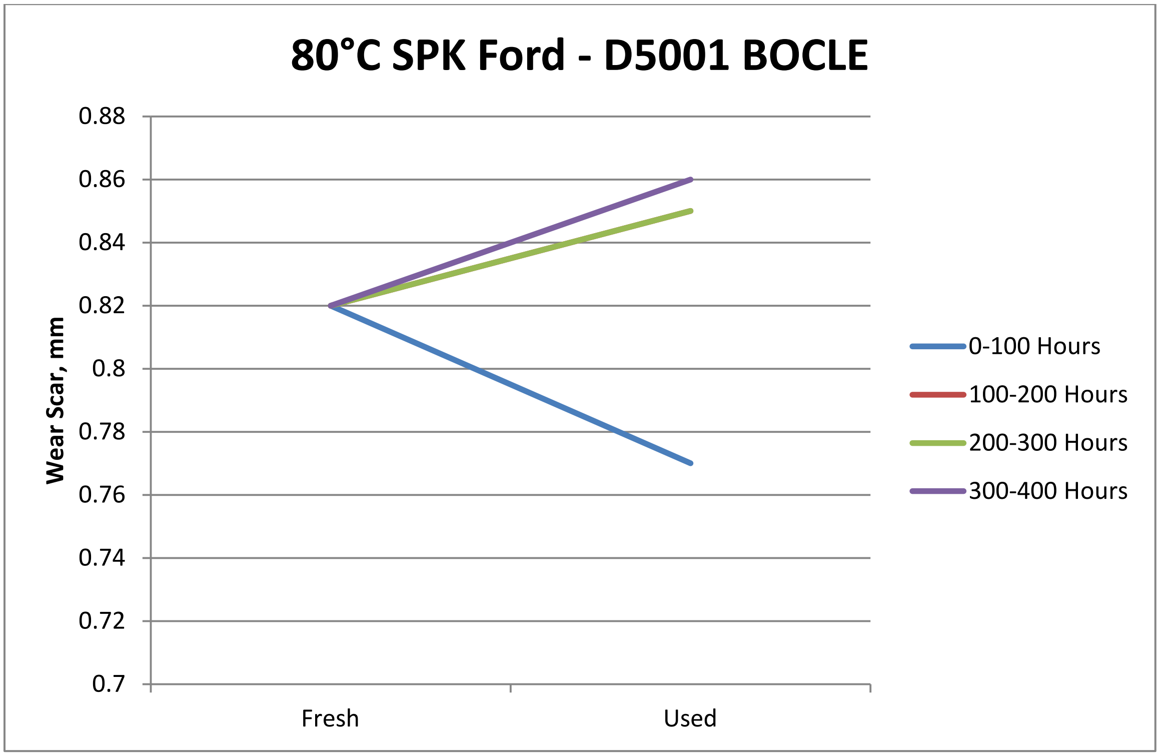

Figure D-7. ASTM D5001 BOCLE

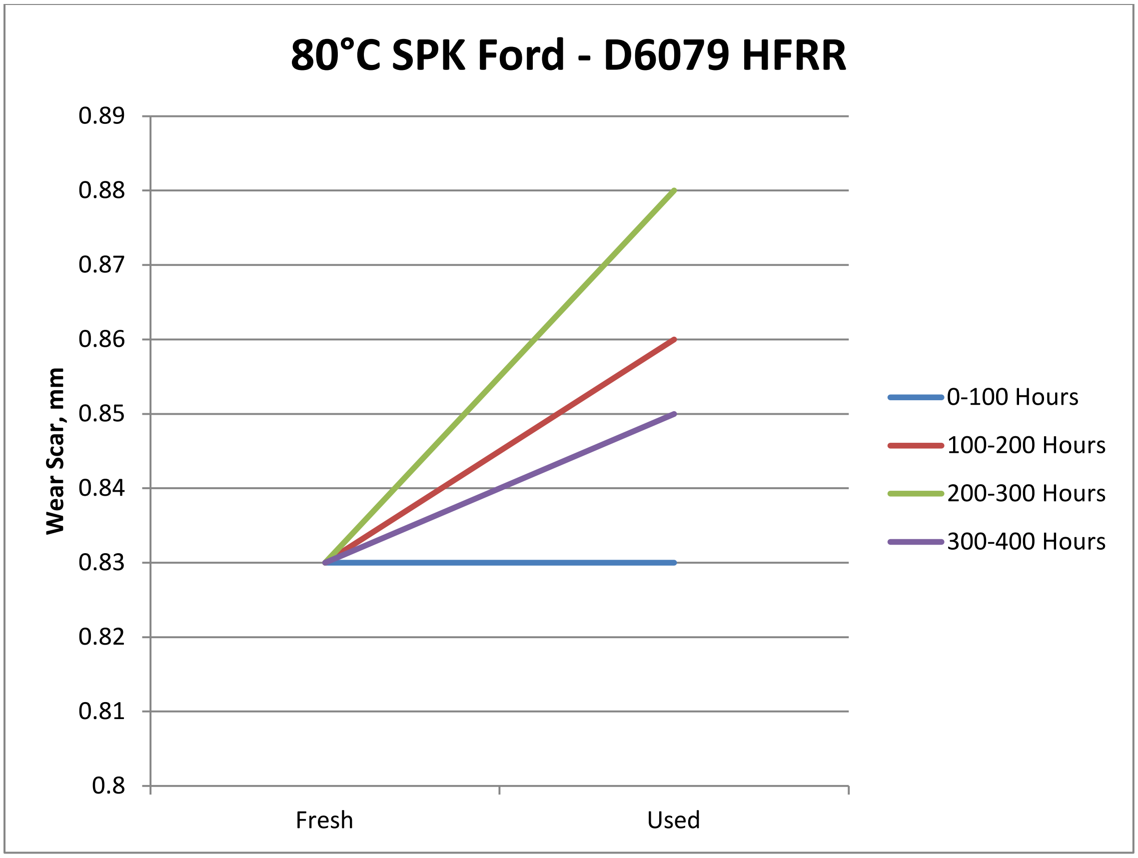

Figure D-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on SPK at 80°C inlet temperature.

Fuel Pump

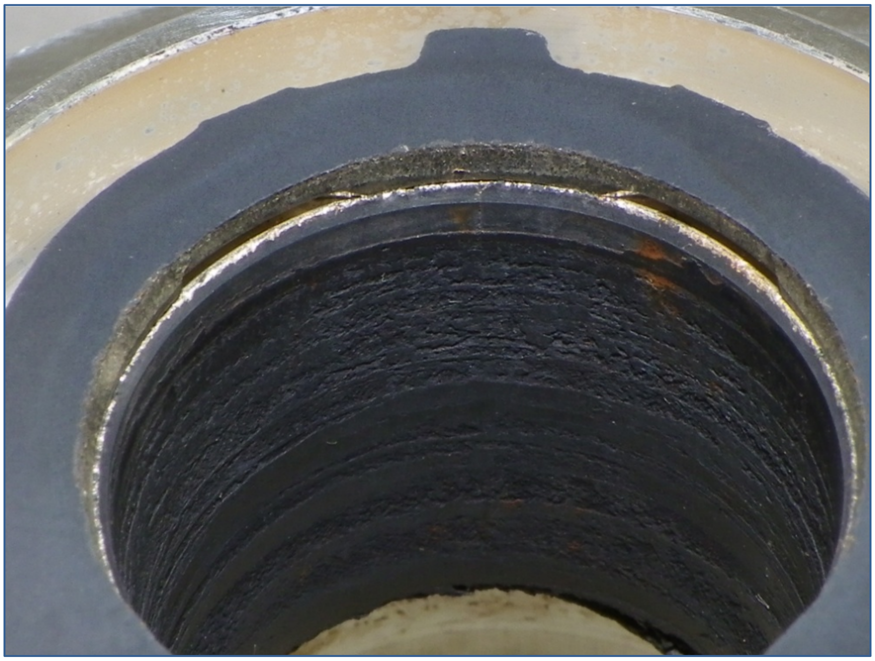

Figure D-9. Front Pump Bushing

Figure D-10. Rear Pump Bushing

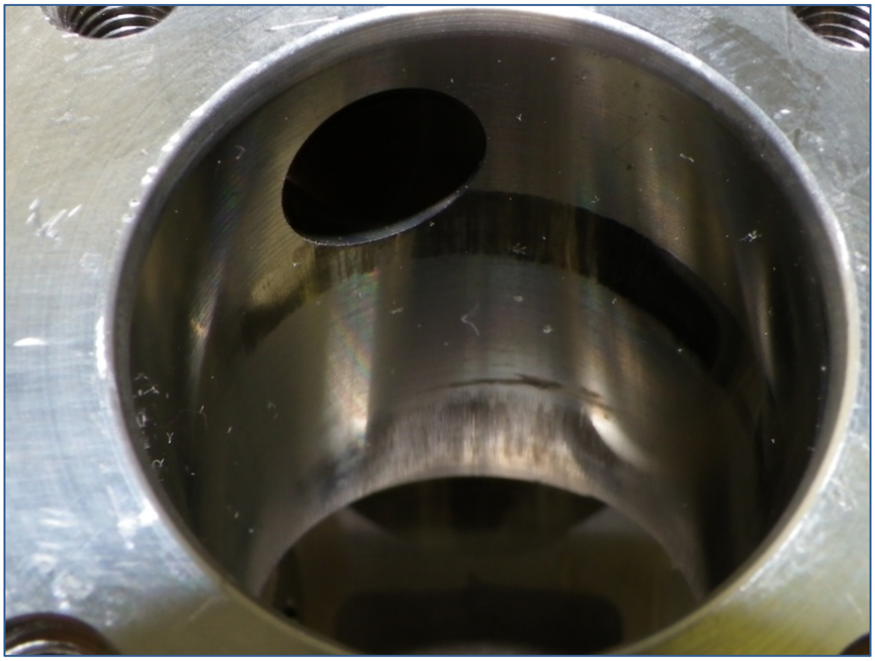

Figure D-11. Left Pump Bore Side 1

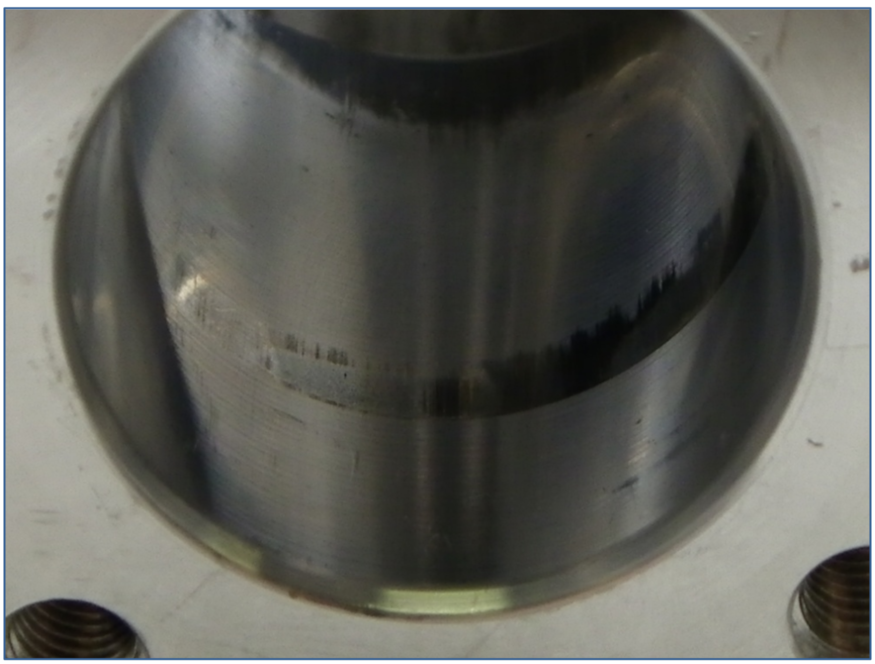

Figure D-12. Left Pump Bored Side 2

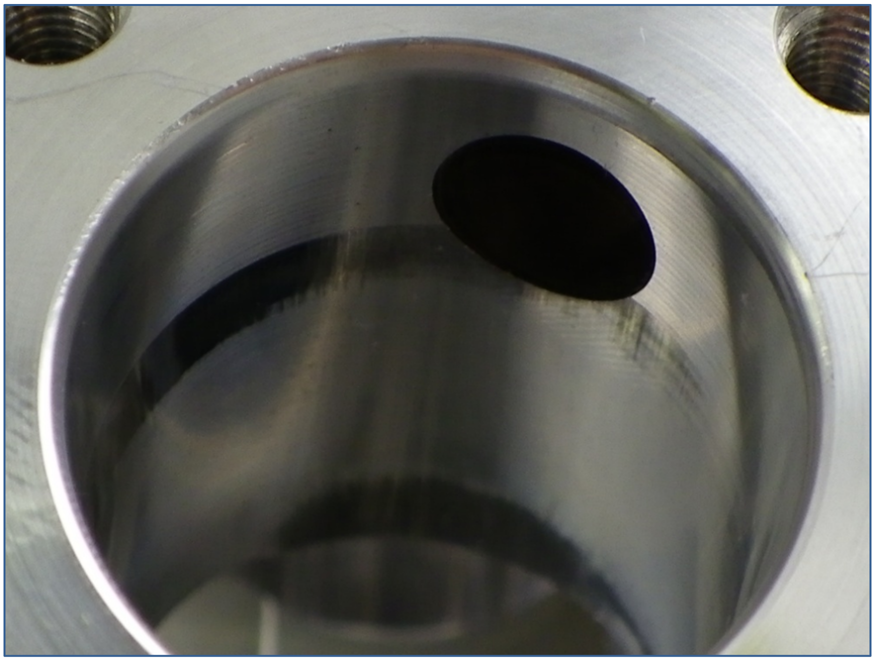

Figure D-13. Right Pump Bore Side 1

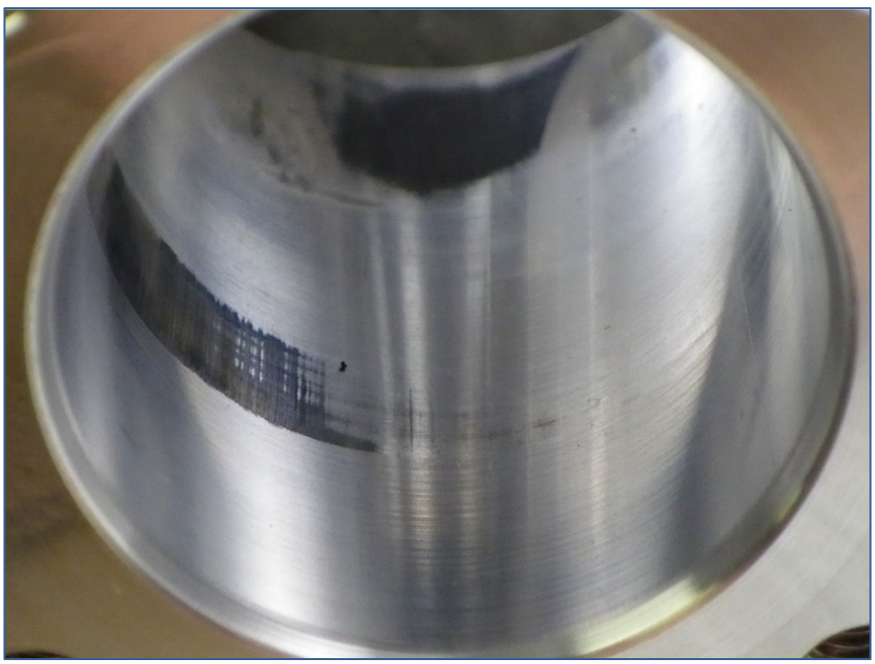

Figure D-14. Right Pump Bore Side 2

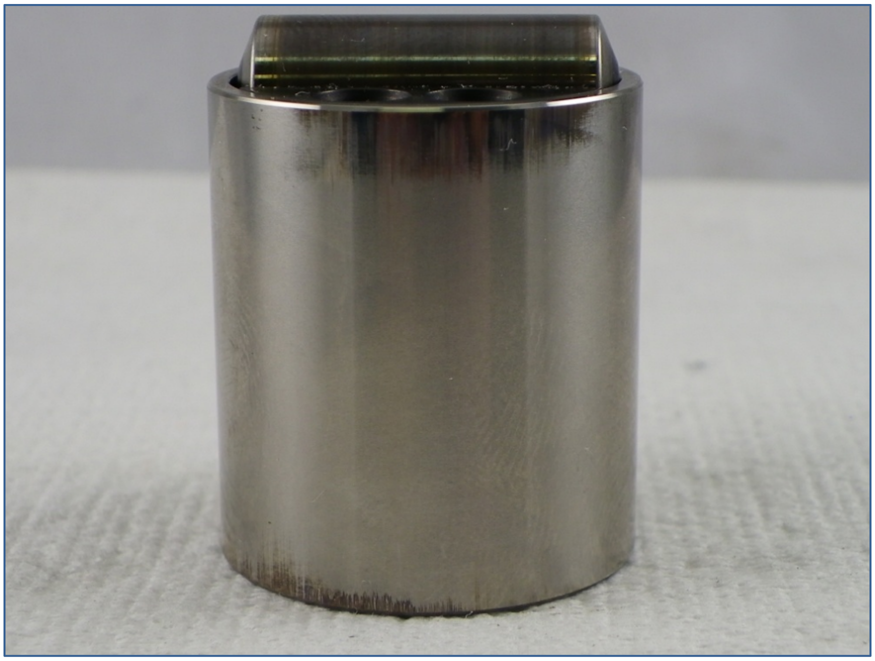

Figure D-15. Left Cam Follower Side 1

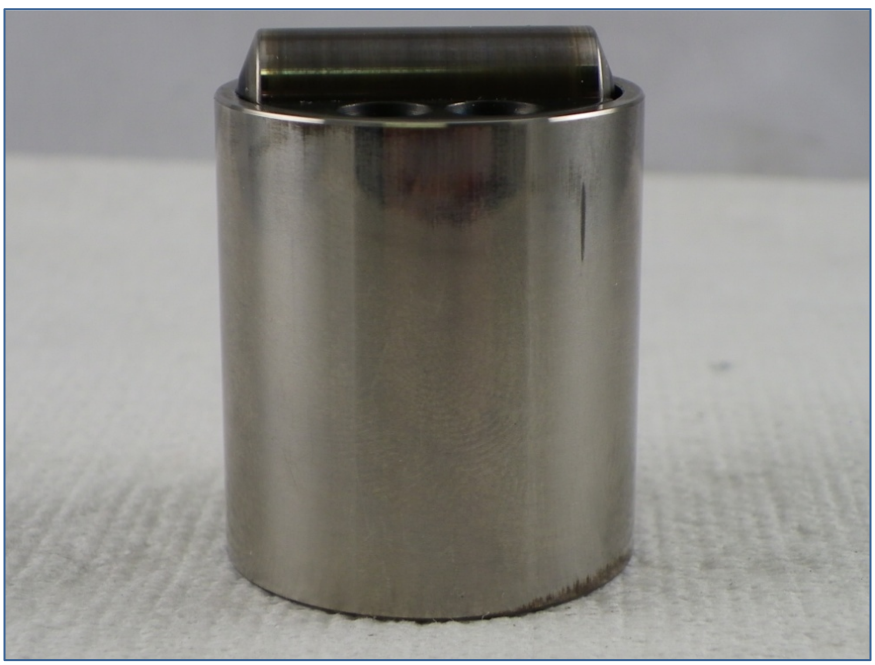

Figure D-16. Left Cam Follower Side 2

Figure D-17. Right Cam Follower Side 1

Figure D-18. Right Cam Follower Side 2

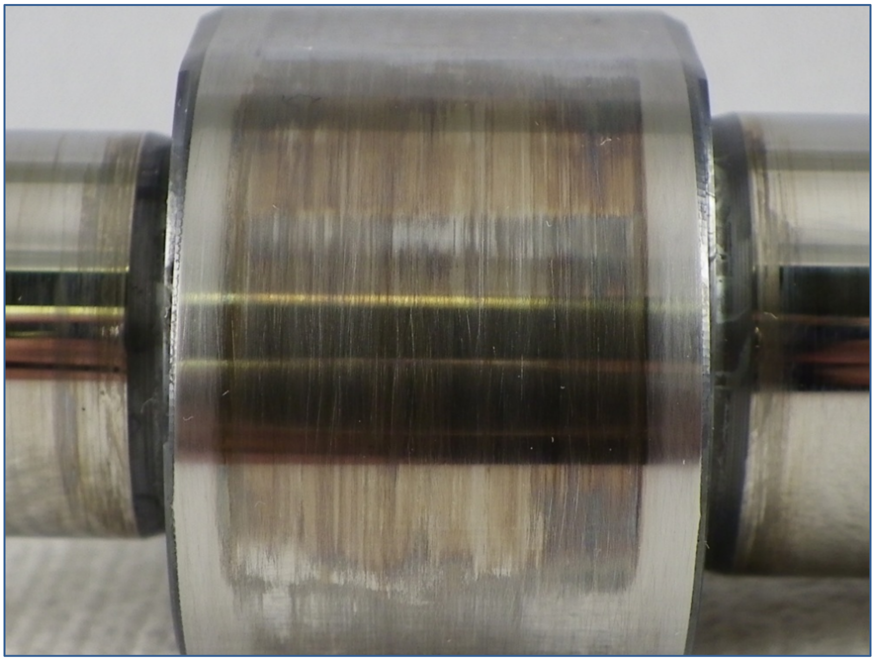

Figure D-19. Camshaft Lobe

Fuel Injector

Figure D-20. Injector Needle

Figure D-21. Upper Hydraulic Coupler Piston Side A

Figure D-22. Upper Hydraulic Coupler Piston Side B

Figure D-23. Lower Hydraulic Coupler Piston Side A

Figure D-24. Lower Hydraulic Coupler Piston Side B

Figure D-25. Intermediate Plate (Top)

Figure D-26. Intermediate Plate (Bottom)

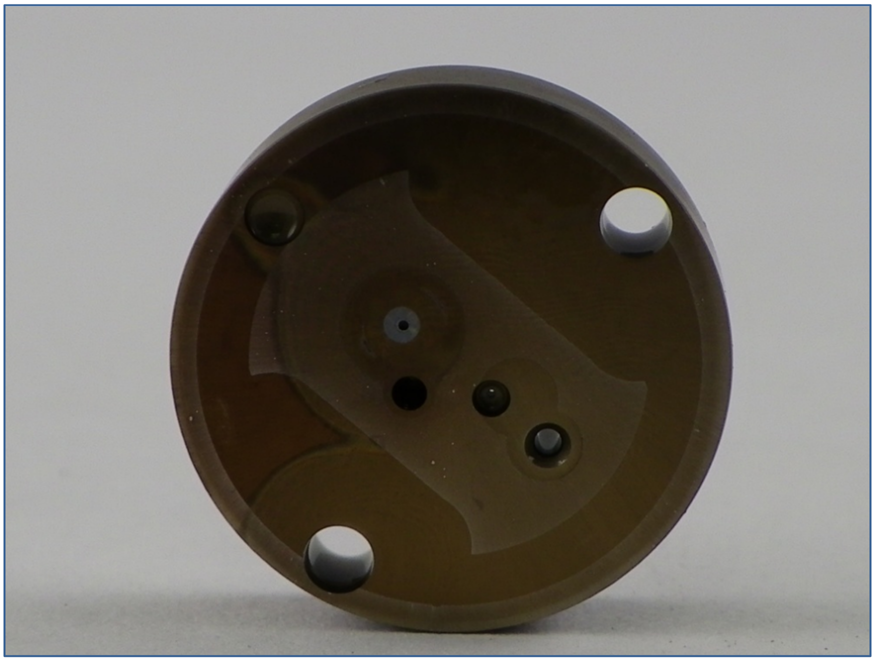

Figure D-27. Control Valve Plate (Top)

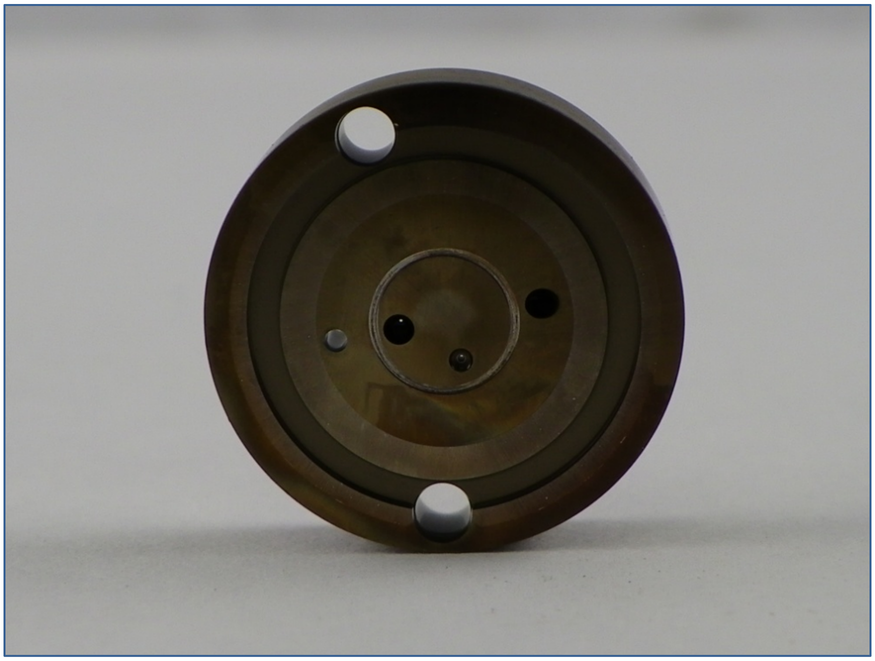

Figure D-28. Control Valve Plate (Bottom)

Figure D-29. Fuel Injector Control Valve

APPENDIX E

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Ford 6.7L Fuel System

Jet A

Jet A-AF8027-60°C-FRD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Ford 6.7L Fuel System

Test Fuel: Jet A
Test Number: Jet A-AF8027-60°C-FRD
Start of Test Date: November 3, 2011
End of Test Date: December 2, 2011
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) conducted a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal was to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI) DCI-4A at a rate of 9 ppm, and a 1:1 blend of Jet A and the synthetic fuel with the CI/LI at rates of 9 ppm and 22.5 ppm. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Five tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and two at 80°C (176 °F), for a total of seven tests. An eighth test was conducted to isolate fuel impact on two critical components. The lower temperature ULSD test was considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Ford 6.7L fuel system manufactured by Bosch. The fuel-lubricated high pressure pump allows the system to reach rail pressures of up to 20,000 psi. It is operated at the same rotational speed as the engine crankshaft for a rated condition of 2800 rpm. Within the pump, the camshaft drives two plungers, oriented in a “V” configuration, which pressurize the fuel entering the rail. Each plunger is driven by two lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure system consists of a lift pump and filter combination to remove large particles and water along with a high efficiency final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Ford 6.7L system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Ford supplied engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The pump consisted of two high strength rods which compressed fuel to reach the desired rail pressure. Fuel then flowed to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled to a consistent temperature, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Table E-1.

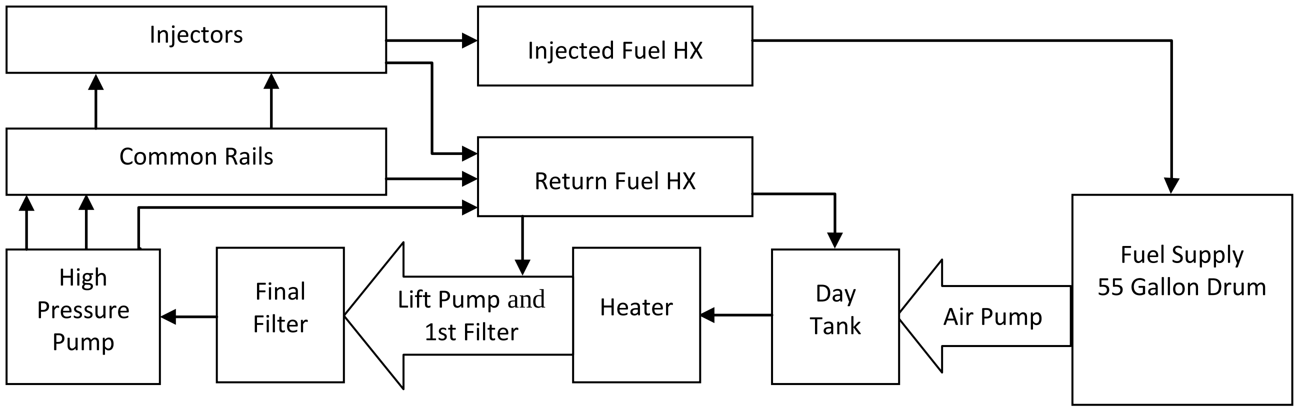

Figure E-1. Ford 6.7L Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table E-1.

Table E-1. NATO Cycle for Ford 6.7L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	600	0	0.5
2	2800	100	2
3	2940	0	0.5
4	2100	100	1
5*	600 to 2800	0 to 100	2
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2
10	1680	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Ford supplied ECM for monitoring purposes. Rail pressures were confirmed using the Ford service tool at various times throughout testing. The system did not experience any performance issues related to rail pressure during the course of the test, Figure E-2.

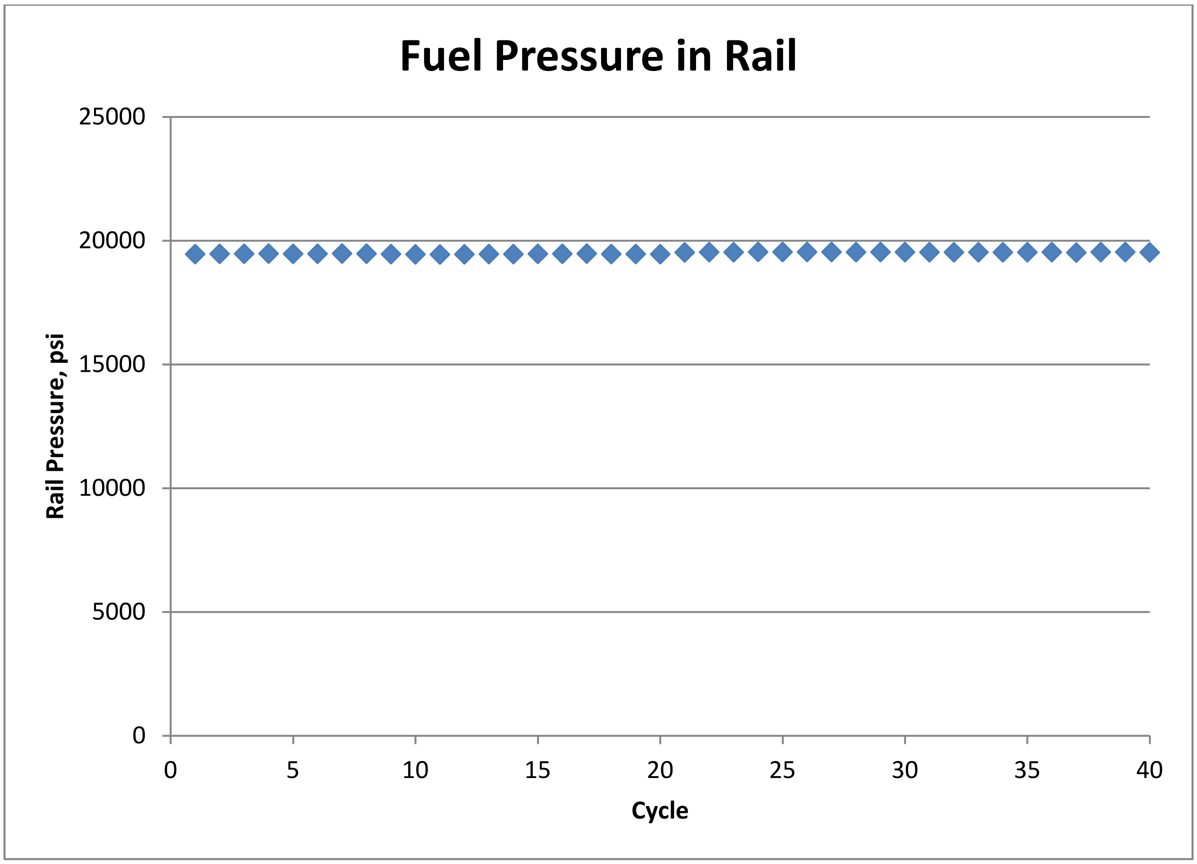

Figure E-2. Fuel Rail Pressure

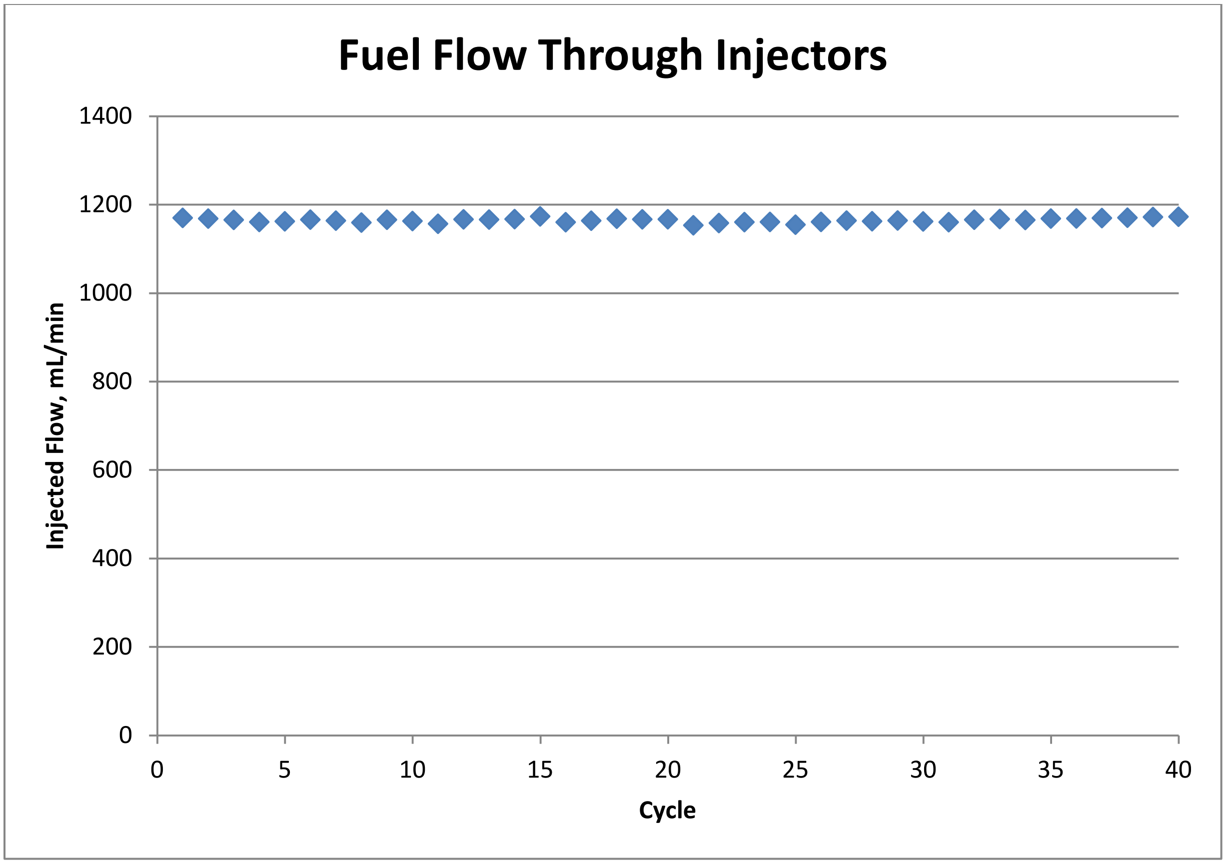

Figure E-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump volume control valve, rail protection check valve, and injector bypass/cooling flow. The variation in flow during cycles seven through 10 was due to an improper controller setting in the fuel heating loop.

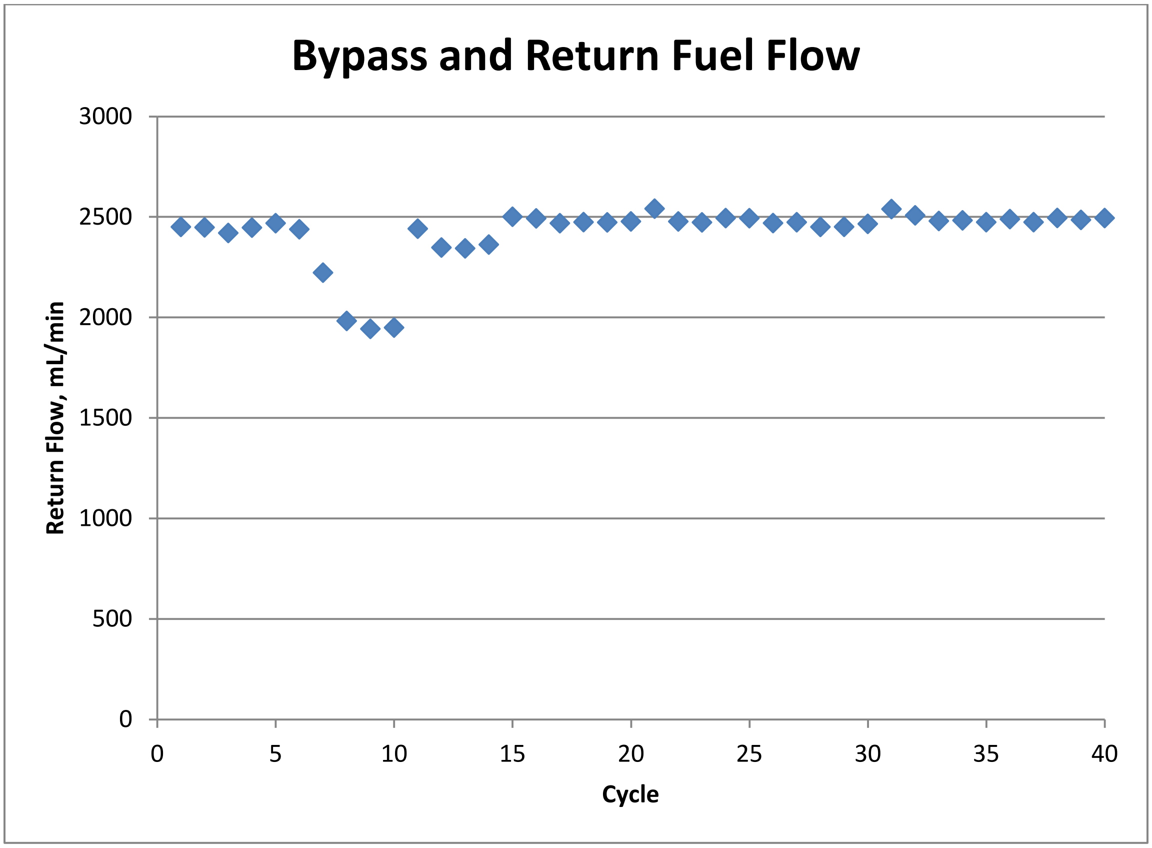

Figure E-4. Return Fuel Flow

The inlet fuel temperature was driven high at one point during the test due to an error in the controller. Parameters had not been fully reset from the previously run test with an 80°C inlet temperature. This was corrected and no further issues were noted over the duration of the test.

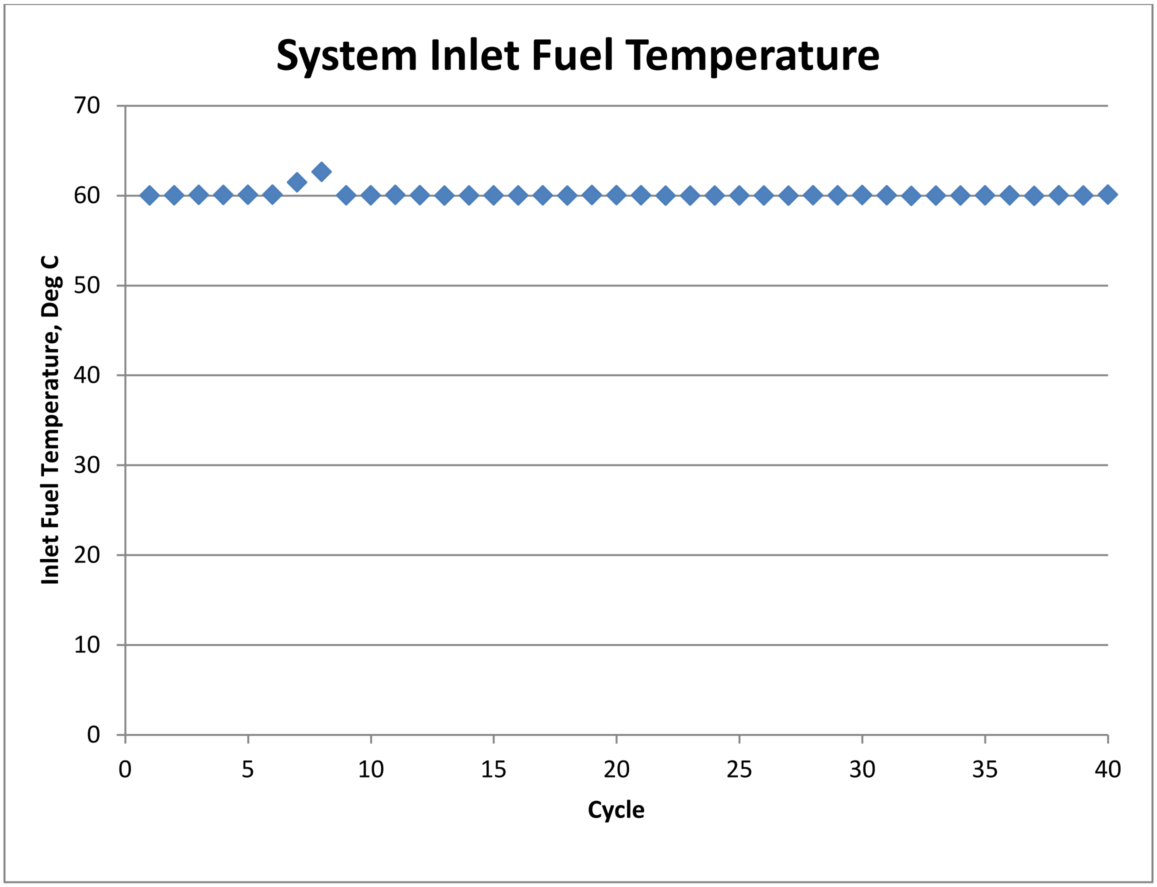

Figure E-5. System Inlet Fuel Temperature

Fuel filter inlet pressure is a measure of the pressure being developed by the lift pump and fuel/water separator unit of the system. There was a dip in filter pressure that corresponded to the deviation in system inlet temperature and bypass flow rate.

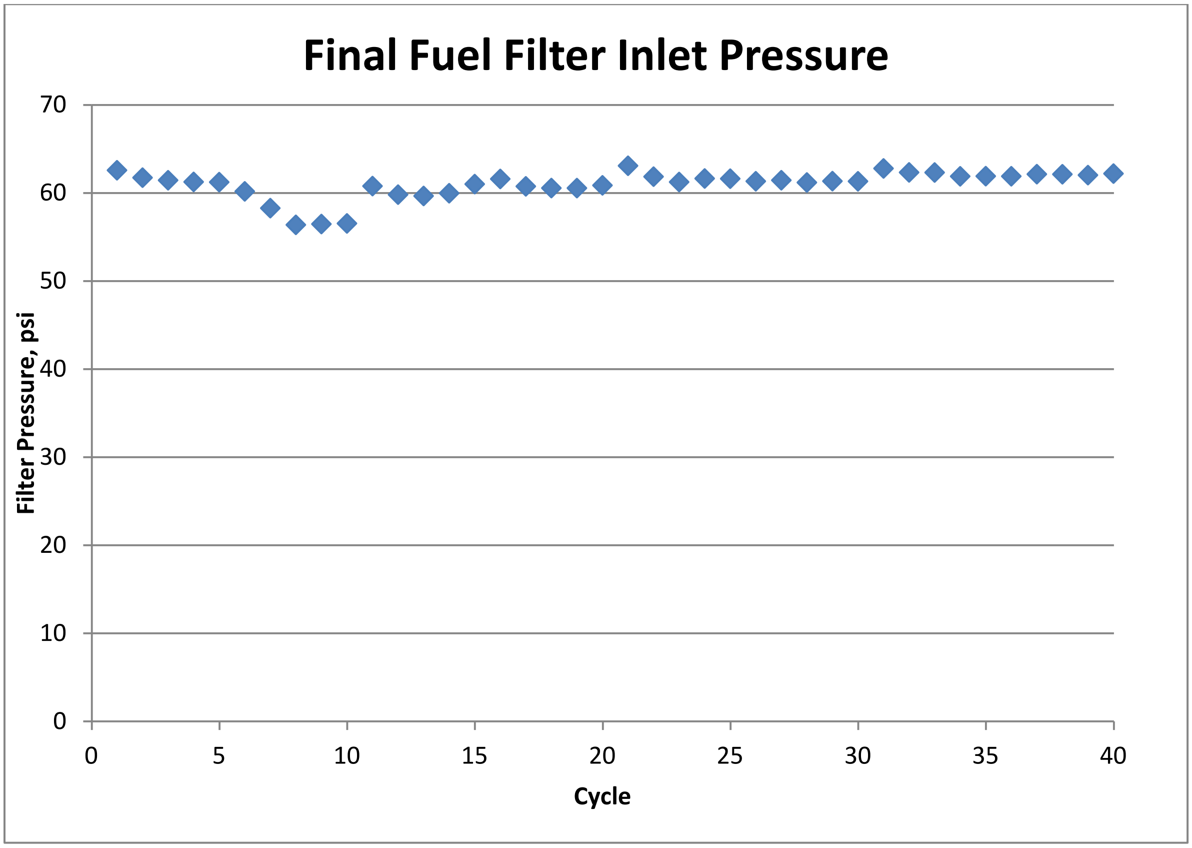

Figure E-6. Fuel Filter Pressure

Table E-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.5	0.9	58.9	63.7
Bypass Fuel Temperature, deg C	63.5	1.7	56.1	67.9
Rail Pressure, psi	19467	44	19312	19606
Injected Flow Rate, mL/min	1165.7	15.5	1129.1	1244.8
Return Fuel Flow Rate, mL/min	2277.4	220.2	1863.8	2486.3
Fuel Filter Inlet Pressure, psi	59.6	2.3	55.8	63.1
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.4	59.1	62.8
Bypass Fuel Temperature, deg C	63.4	0.5	57.7	64.6
Rail Pressure, psi	19460	48	19315	19609
Injected Flow Rate, mL/min	1166.9	16.2	1126.6	1250.5
Return Fuel Flow Rate, mL/min	2438.6	61.3	2316.4	2547.6
Fuel Filter Inlet Pressure, psi	60.6	0.6	59.4	62.1
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.4	58.8	62.5
Bypass Fuel Temperature, deg C	62.9	0.6	58.5	63.8
Rail Pressure, psi	19538	44	19400	19712
Injected Flow Rate, mL/min	1161.4	15.3	1129.2	1248.7
Return Fuel Flow Rate, mL/min	2479.3	26.4	2428.0	2557.4
Fuel Filter Inlet Pressure, psi	61.6	0.6	60.7	63.3
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.4	58.7	62.1
Bypass Fuel Temperature, deg C	62.1	0.5	57.2	63.4
Rail Pressure, psi	19532	44	19374	19705
Injected Flow Rate, mL/min	1169.3	16.7	1124.5	1249.2
Return Fuel Flow Rate, mL/min	2492.4	19.4	2451.4	2552.0
Fuel Filter Inlet Pressure, psi	62.2	0.3	61.5	63.1

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figure E7 and Figure E8. It should be noted that the final values for 200, 300, and 400 hour BOCLE tests were the same.

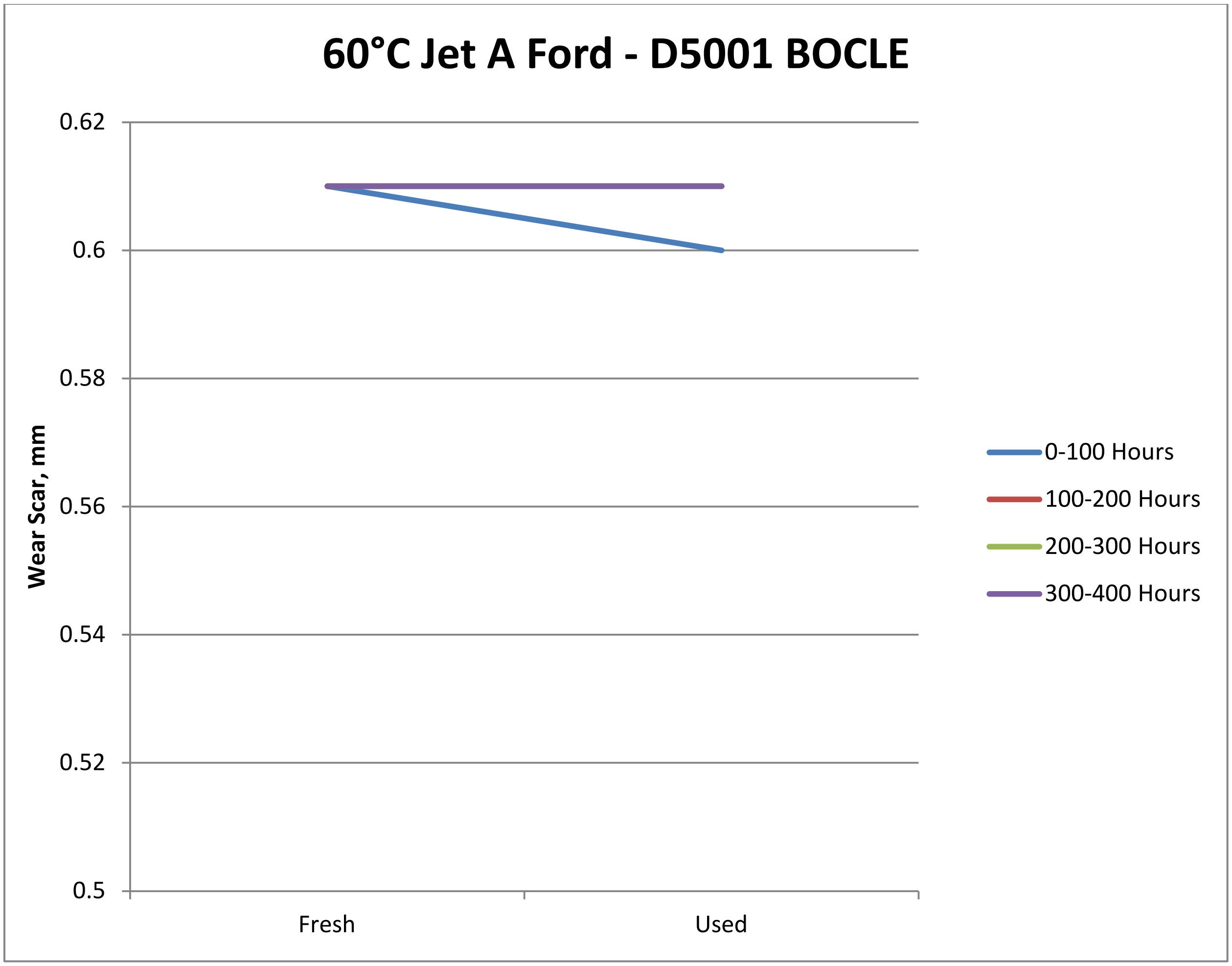

Figure E-7. ASTM D5001 BOCLE

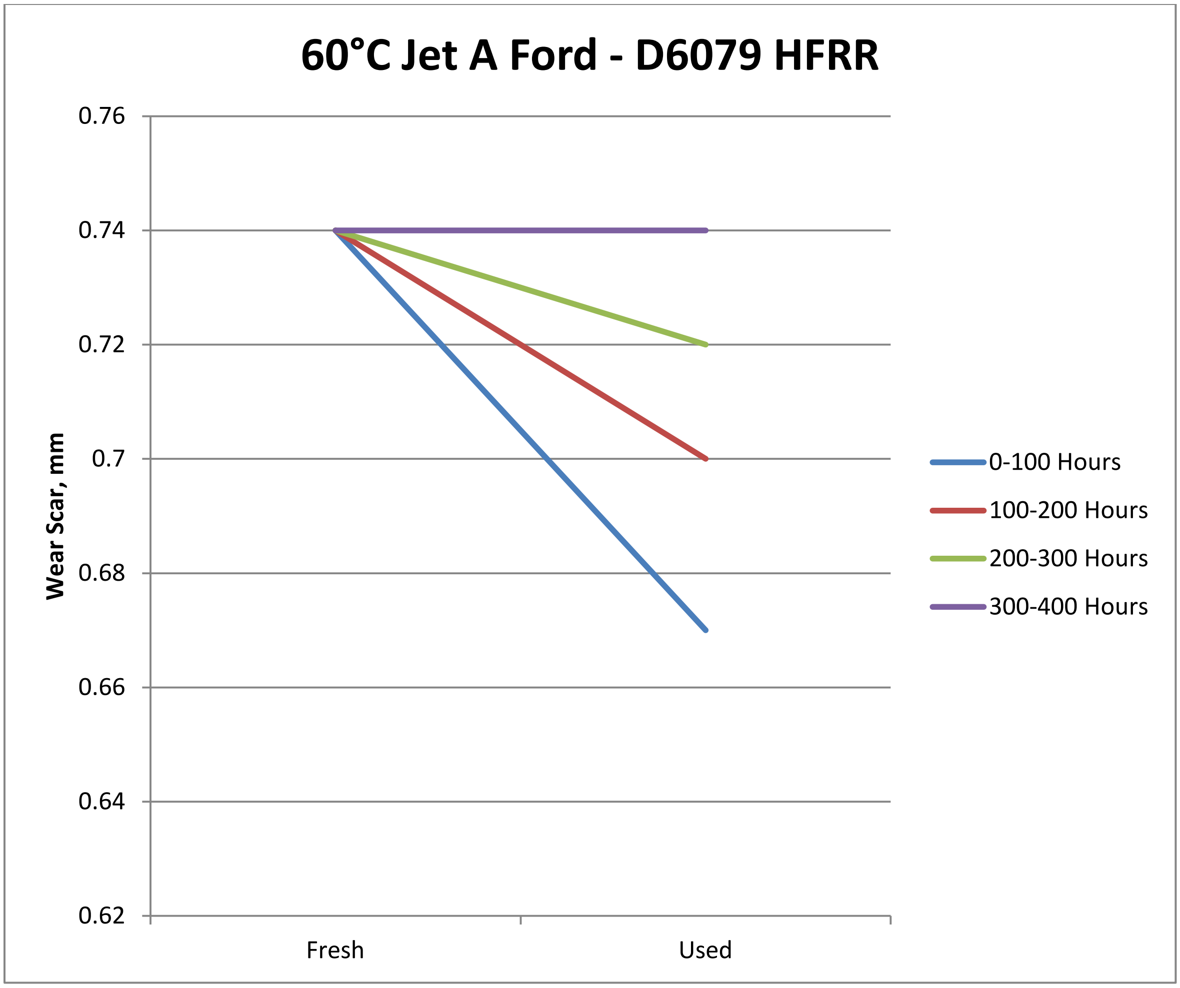

Figure E-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on Jet A at 60°C inlet temperature.

Fuel Pump

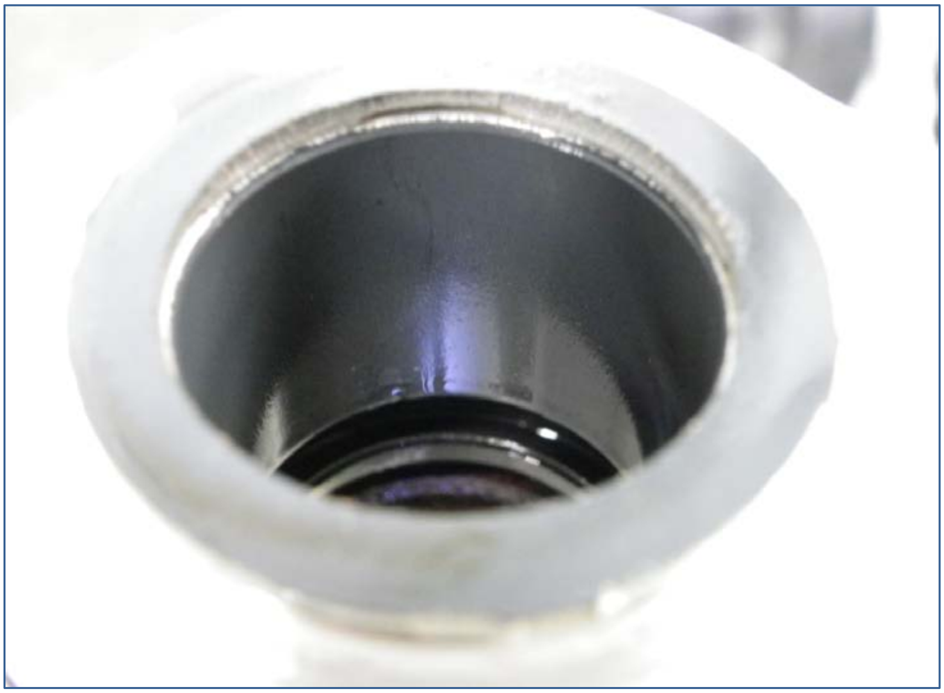

Figure E-9. Front Pump Bushing at 200 Hours

Figure E-10. Front Pump Bushing at 400 Hours

Figure E-11. Rear Pump Bushing

Figure E-12. Left Pump Bore Side 1 Upper

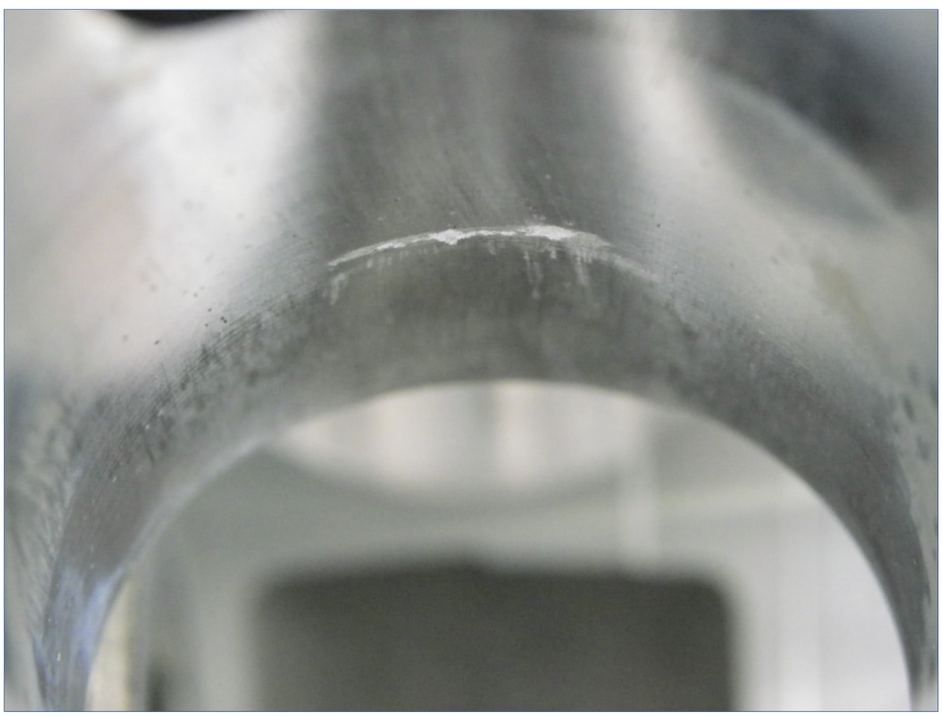

Figure E-13. Left Pump Bore Side 1 Lower

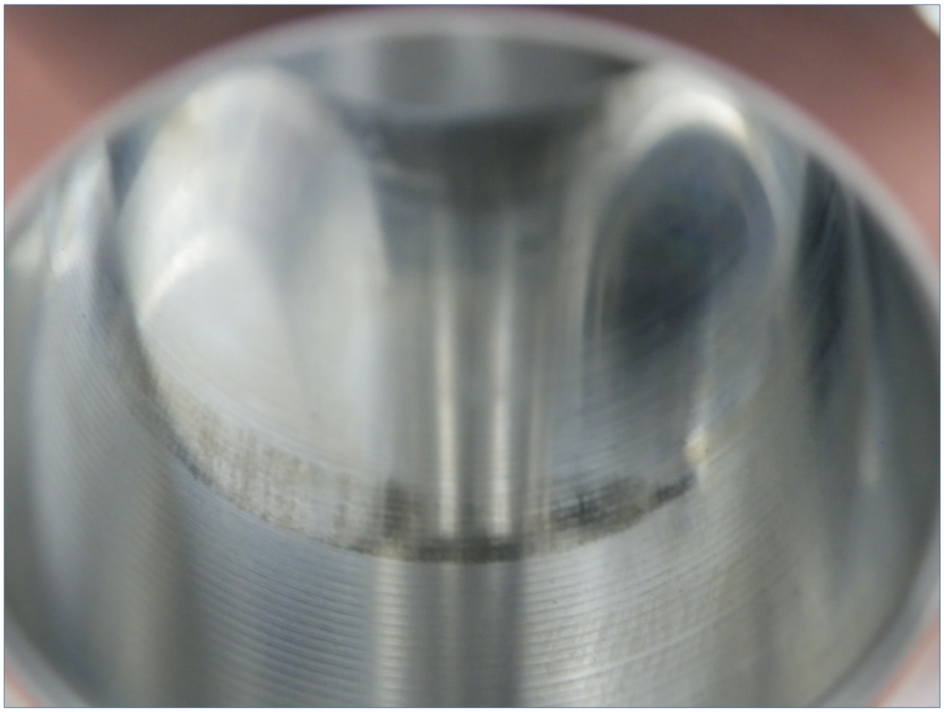

Figure E-14. Left Pump Bore Side 2

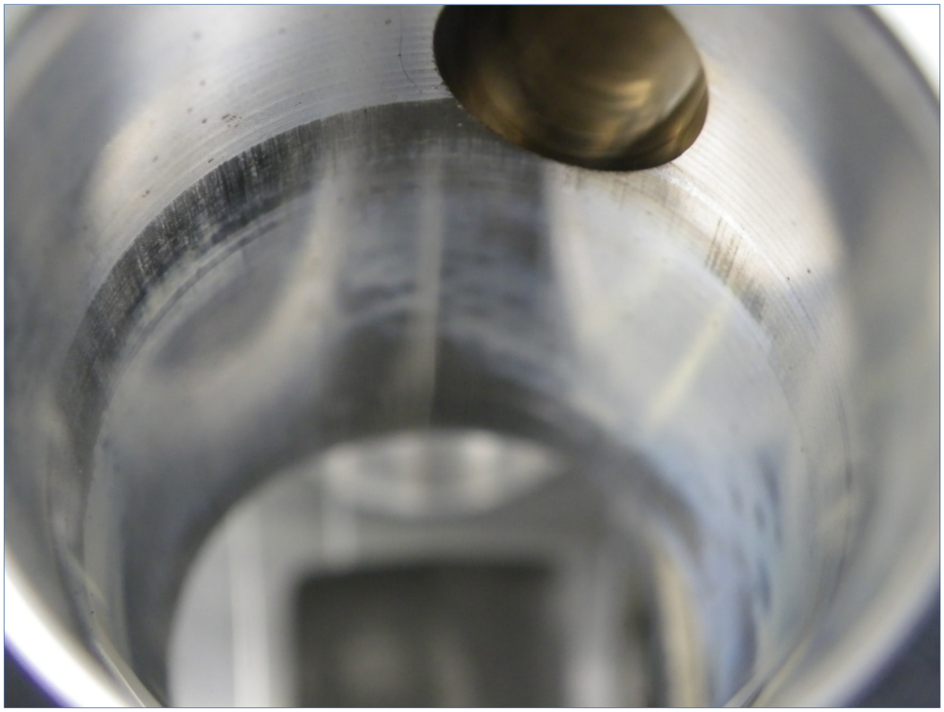

Figure E-15. Right Pump Bore Side 1 Upper

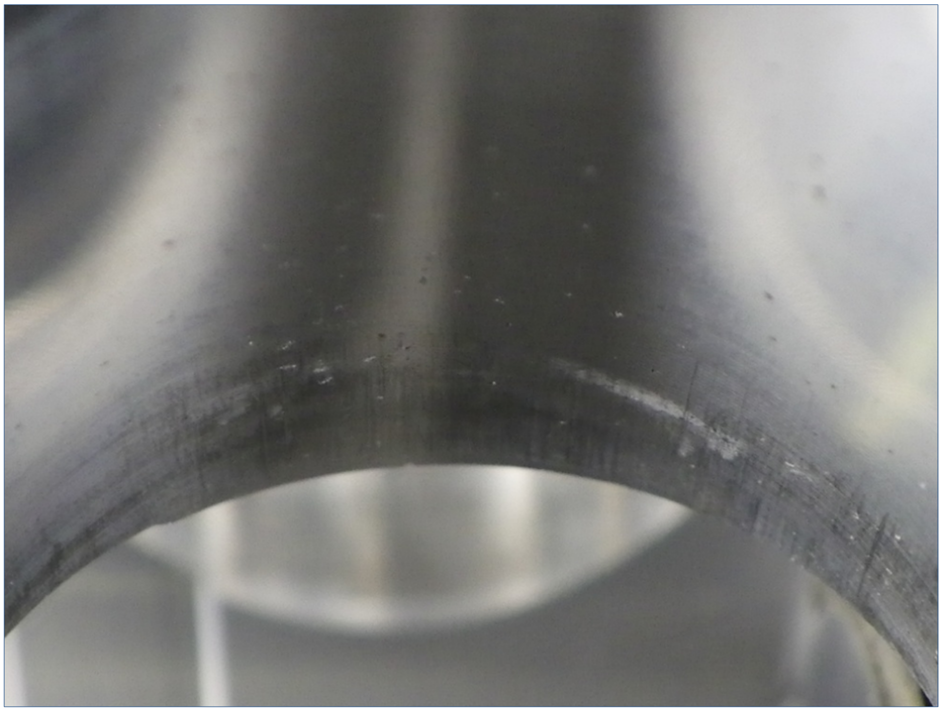

Figure E-16. Right Pump Bore Side 1 Lower

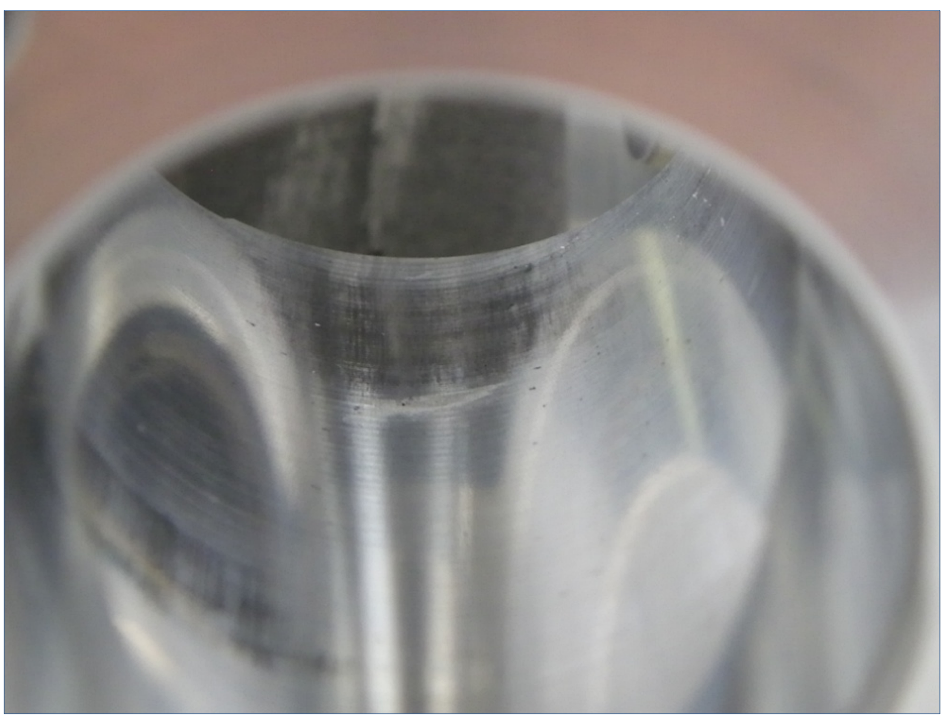

Figure E-17. Right Pump Bore Side 2

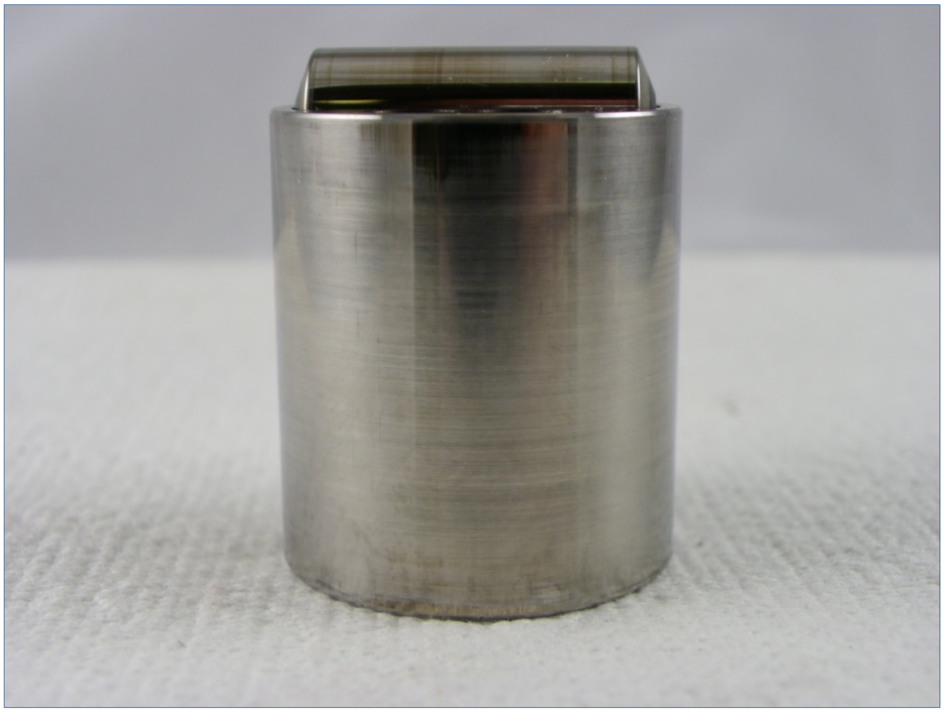

Figure E-18. Left Cam Follower Side 1

Figure E-19. Left Cam Follower Side 2

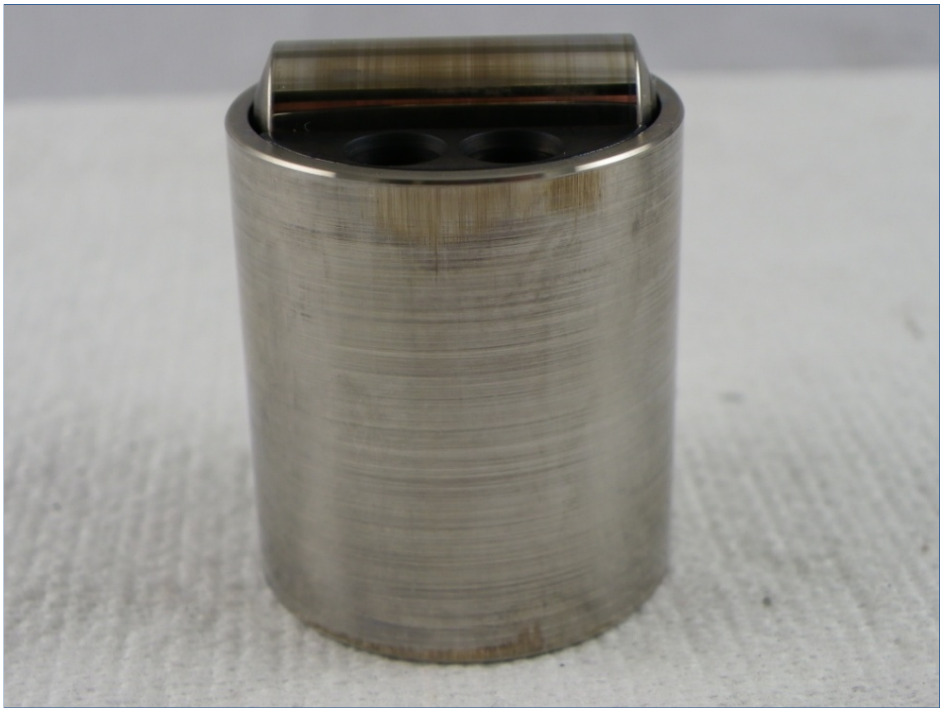

Figure E-20. Right Cam Follower Side 1

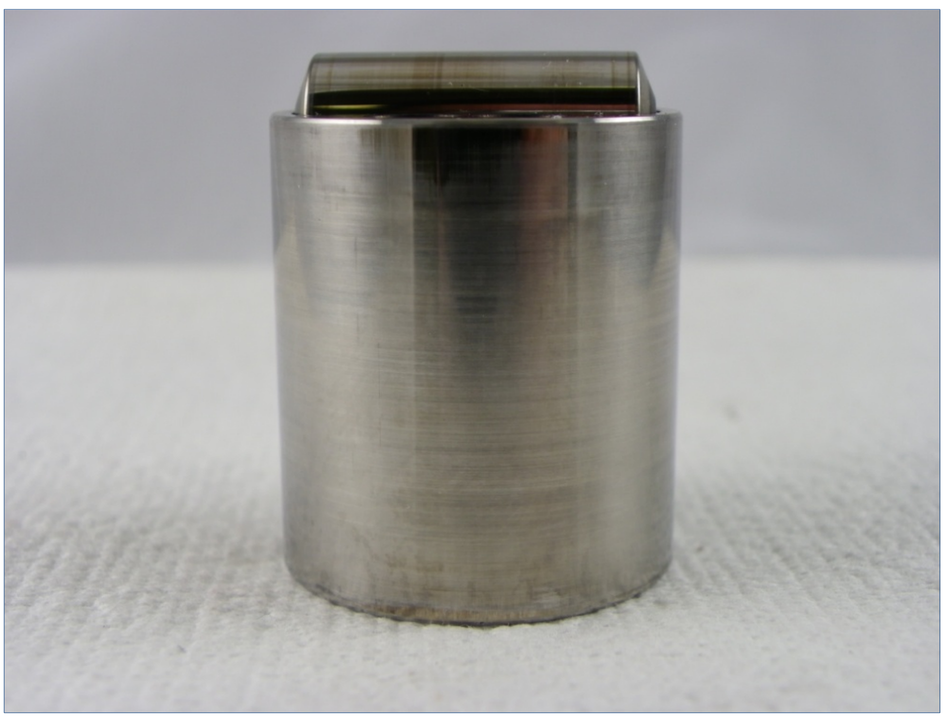

Figure E-21. Right Cam Follower Side 2

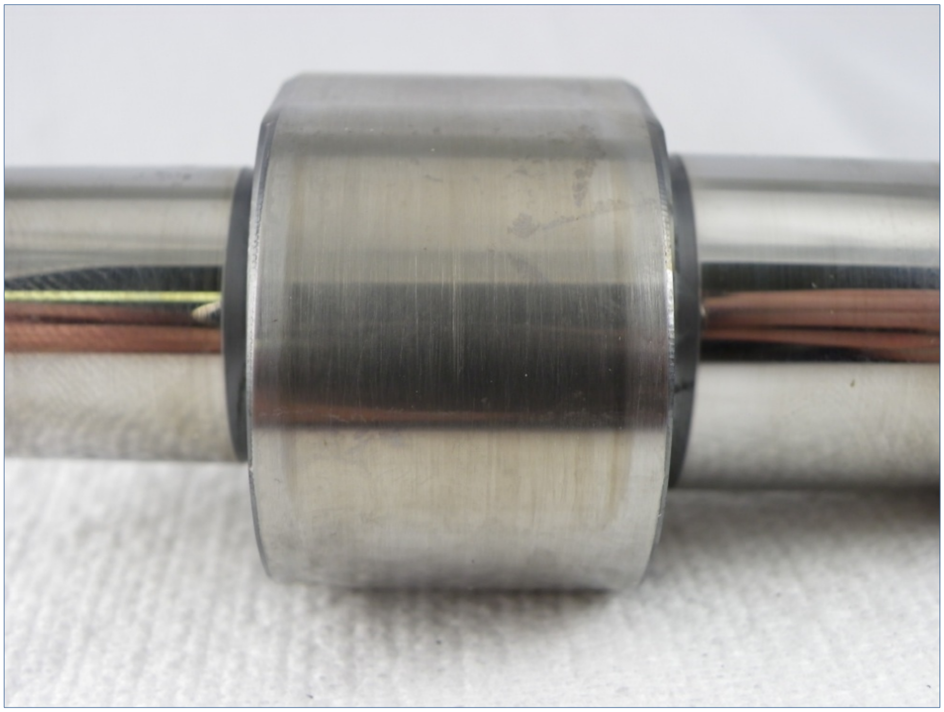

Figure E-22. Camshaft Lobe

Fuel Injector

Figure E-23. Injector Needle

Figure E-24. Upper Hydraulic Coupler Piston Side A

Figure E-25. Upper Hydraulic Coupler Piston Side B

Figure E-26. Lower Hydraulic Coupler Piston Side A

Figure E-27. Lower Hydraulic Coupler Piston Side B

Figure E-28. Intermediate Plate (Top)

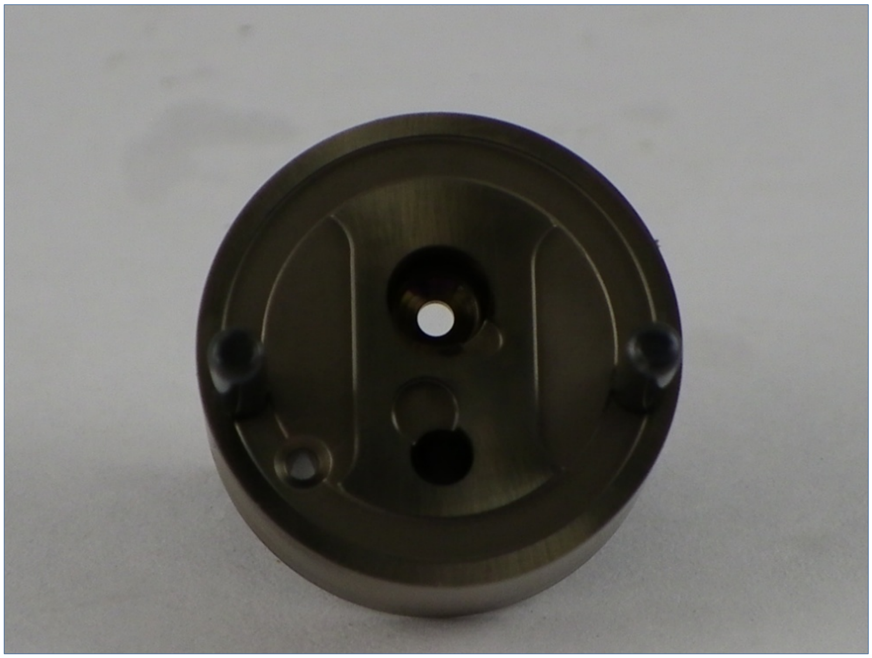

Figure E-29. Intermediate Plate (Bottom)

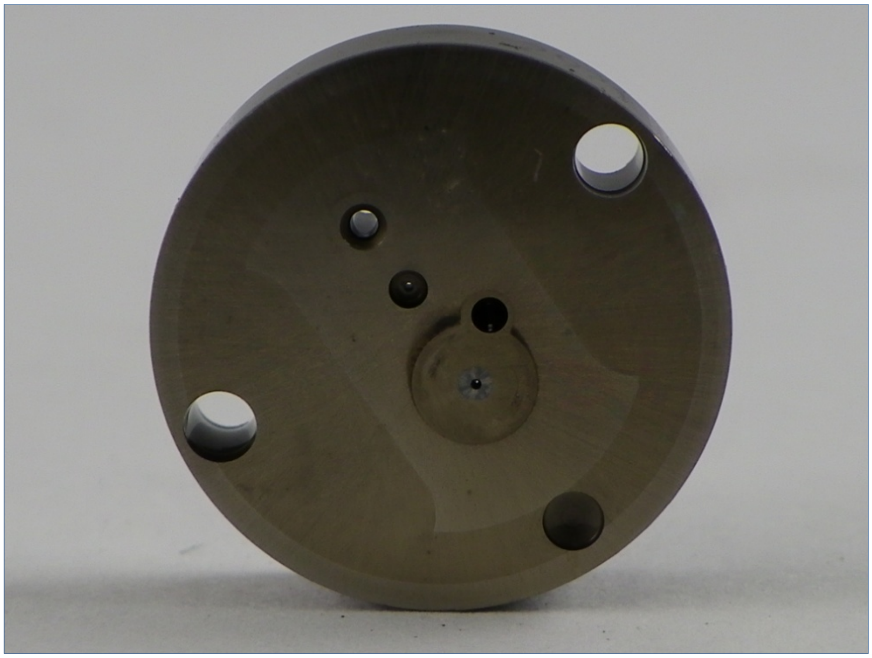

Figure E-30. Control Valve Plate (Top)

Figure E-31. Control Valve Plate (Bottom)

Figure E-32. Fuel Injector Control Valve

APPENDIX F

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Ford 6.7L Fuel System

Jet A
Jet A-AF8027-80°C-FRD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Ford 6.7L Fuel System

Test Fuel: Jet A
Test Number: Jet A-AF8027-80°C-FRD
Start of Test Date: December 7, 2011
End of Test Date: January 9, 2012
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) conducted a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal was to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI) DCI-4A at a rate of 9 ppm, and a 1:1 blend of Jet A and the synthetic fuel with the CI/LI at rates of 9 ppm and 22.5 ppm. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Five tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and two at 80°C (176 °F), for a total of seven tests. An eighth test was conducted to isolate fuel impact on two critical components. The lower temperature ULSD test was considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Ford 6.7L fuel system manufactured by Bosch. The fuel-lubricated high pressure pump allows the system to reach rail pressures of up to 20,000 psi. It is operated at the same rotational speed as the engine crankshaft for a rated condition of 2800 rpm. Within the pump, the camshaft drives two plungers, oriented in a “V” configuration, which pressurize the fuel entering the rail. Each plunger is driven by two lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure system consists of a lift pump and filter combination to remove large particles and water along with a high efficiency final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Ford 6.7L system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Ford supplied engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The pump consisted of two high strength rods which compressed fuel to reach the desired rail pressure. Fuel then flowed to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled to a consistent temperature, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Figure F-1.

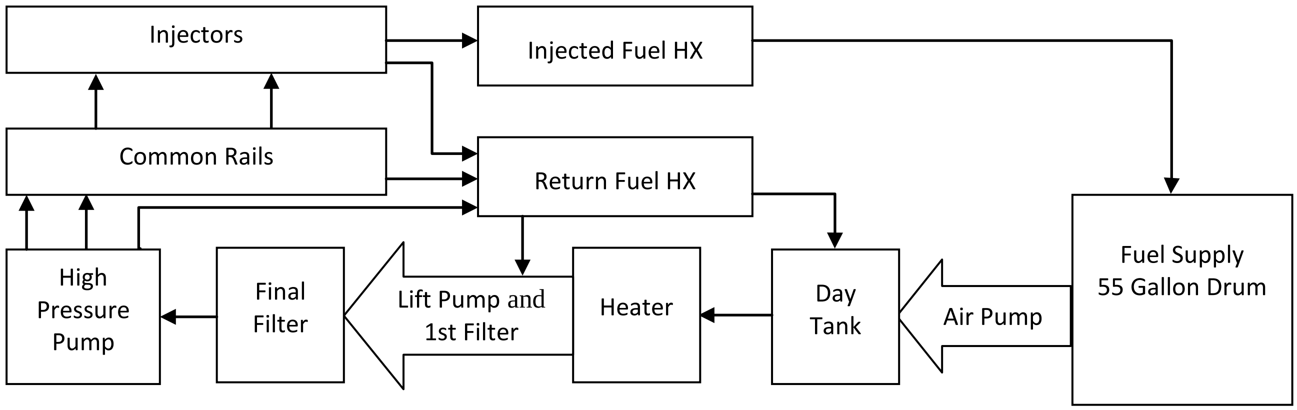

Figure F-1. Ford 6.7L Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table F-1.

Table F-1. NATO Cycle for Ford 6.7L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	600	0	0.5
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4	2100	100	1
5*	600 to 2800	0 to 100	2
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2
10	1680	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Ford supplied ECM for monitoring purposes. Rail pressures were confirmed using the Ford service tool at various times throughout testing. The system did not experience any performance issues related to rail pressure during the course of the test, Figure F-2.

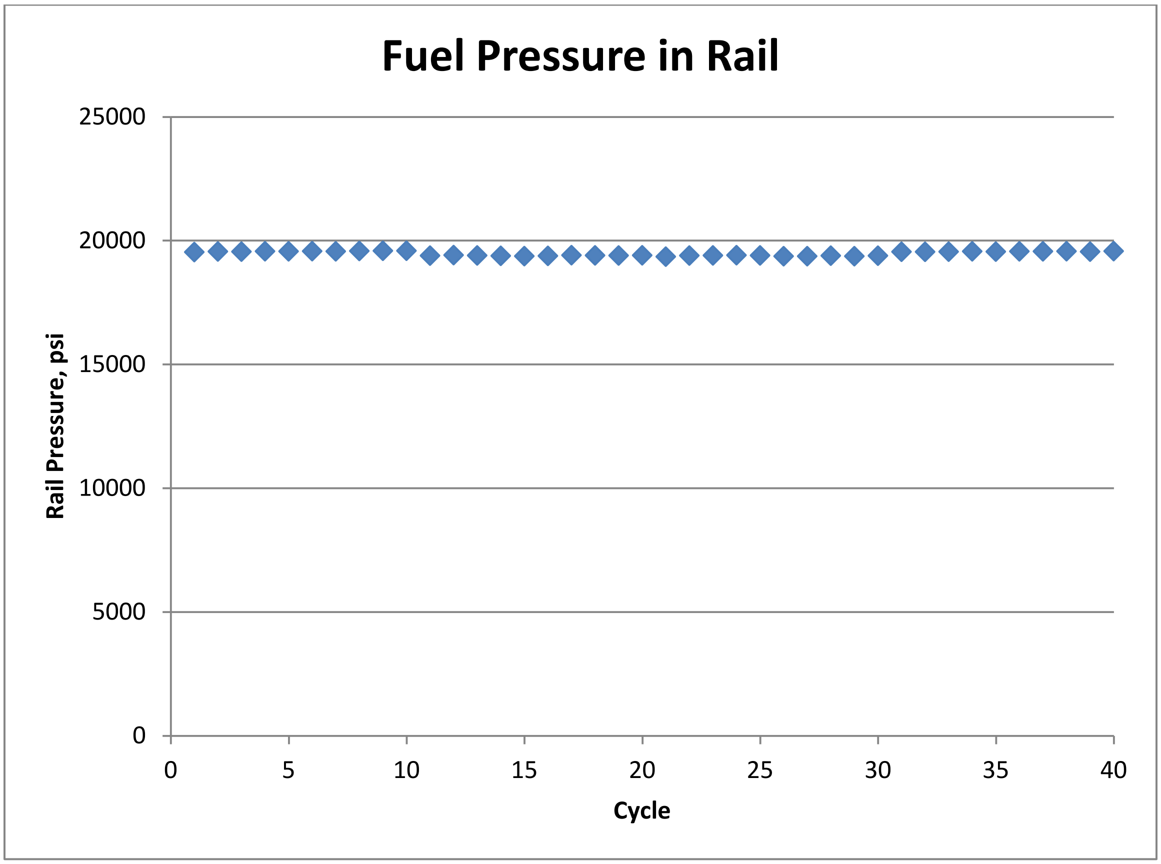

Figure F-2. Fuel Rail Pressure

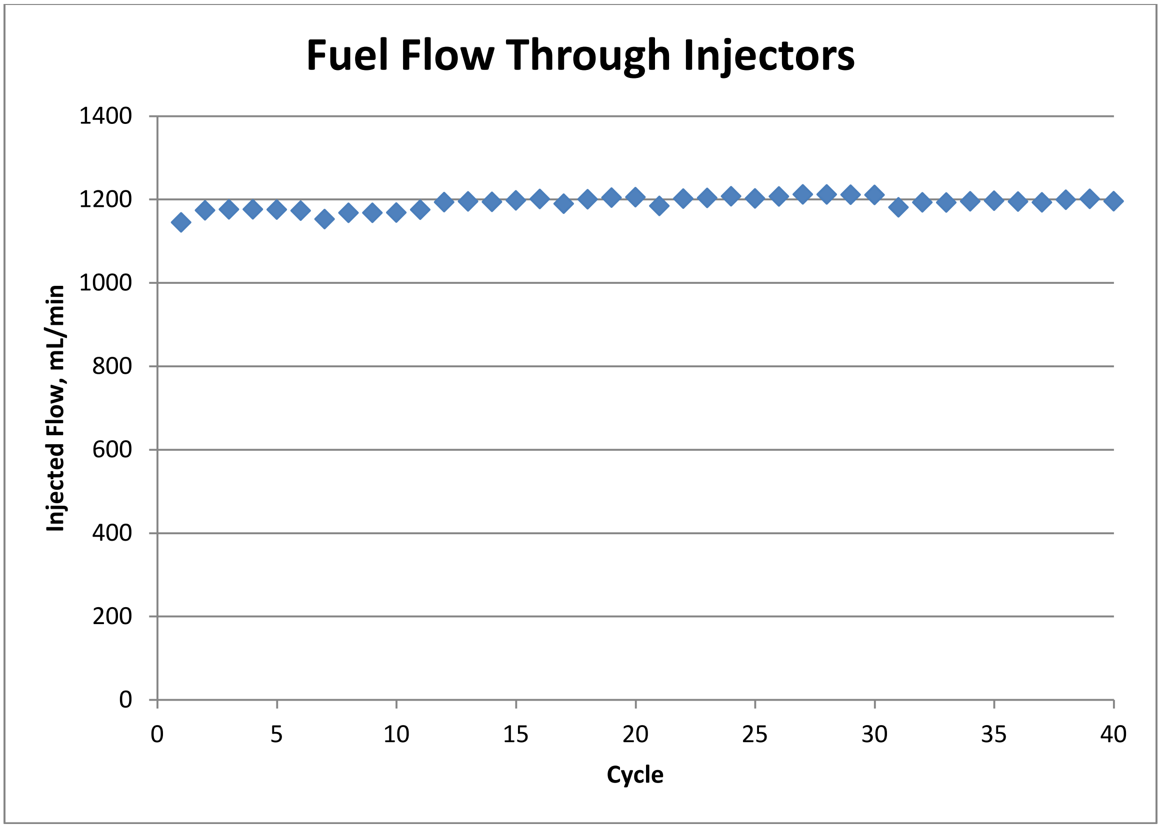

Figure F-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump volume control valve, rail protection check valve, and injector bypass/cooling flow. After an initial break-in period, there was a gradual increase in return fuel flow over the course of the test.

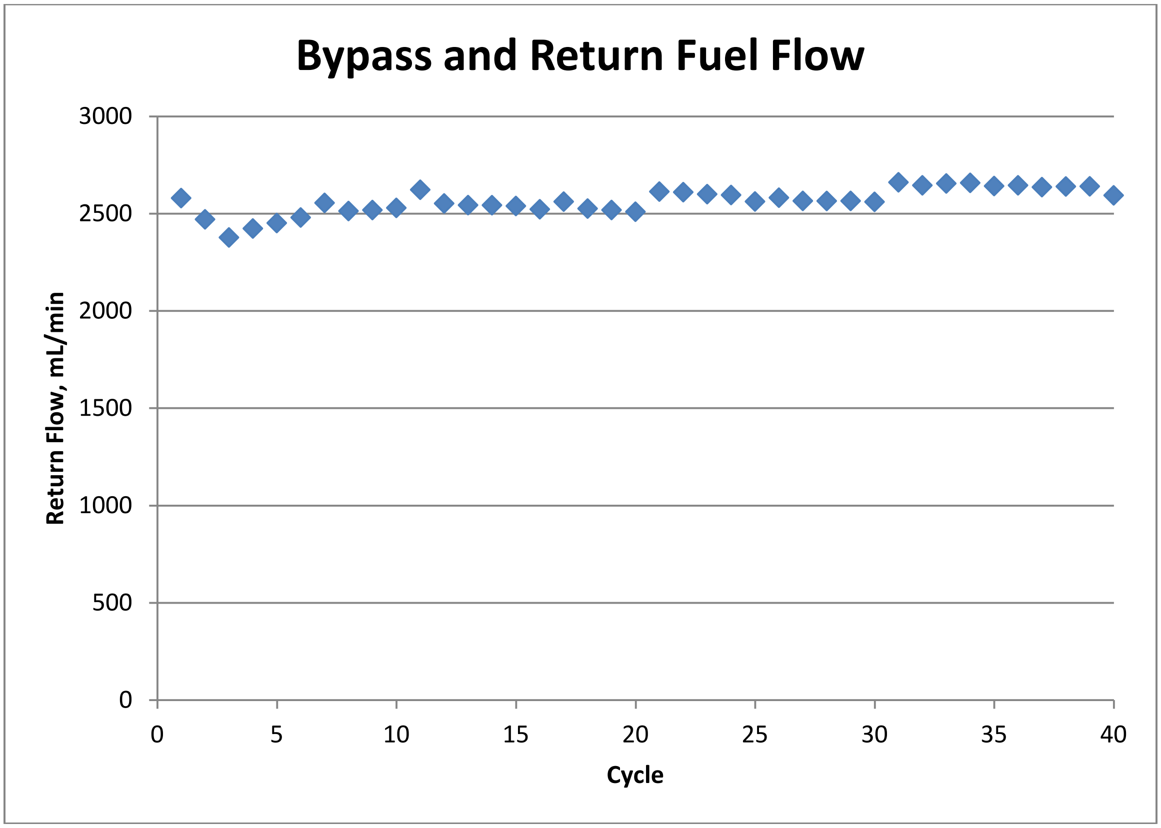

Figure F-4. Return Fuel Flow

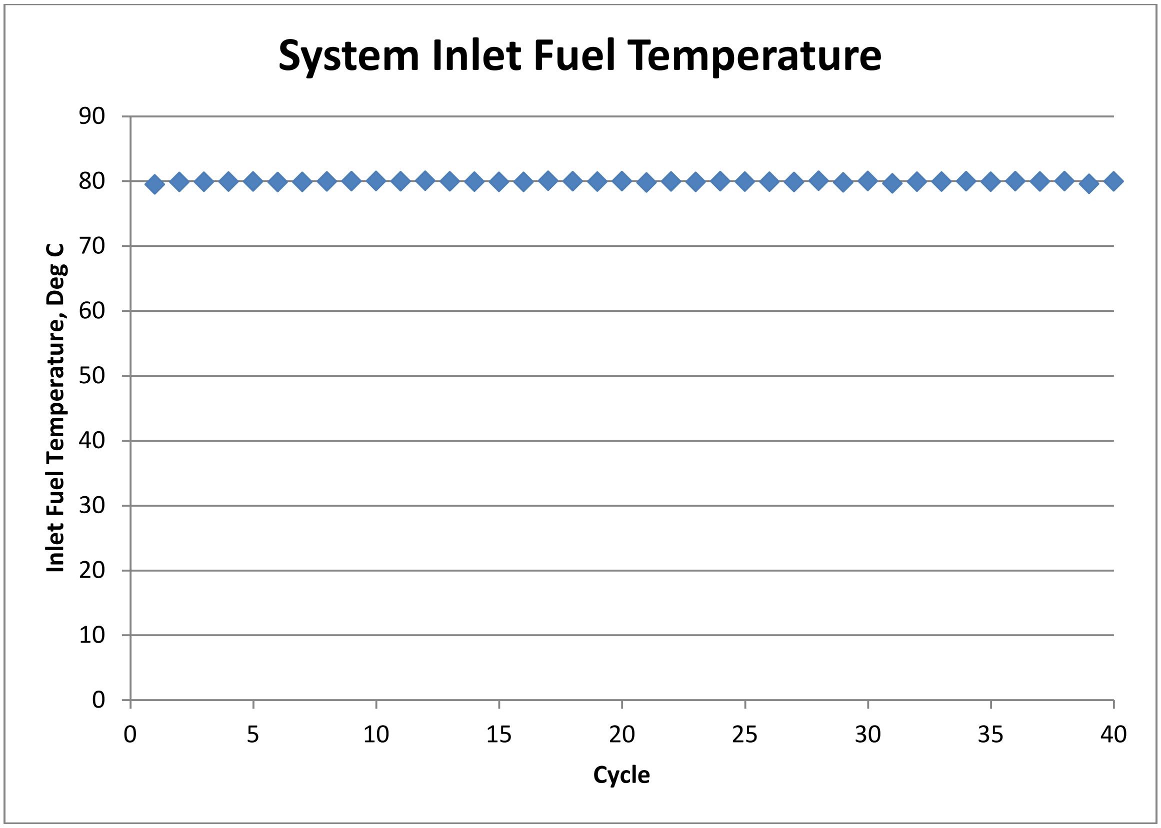

Figure F-5. System Inlet Fuel Temperature

Fuel filter inlet pressure is a measure of the pressure being developed by the lift pump and fuel/water separator unit of the system.

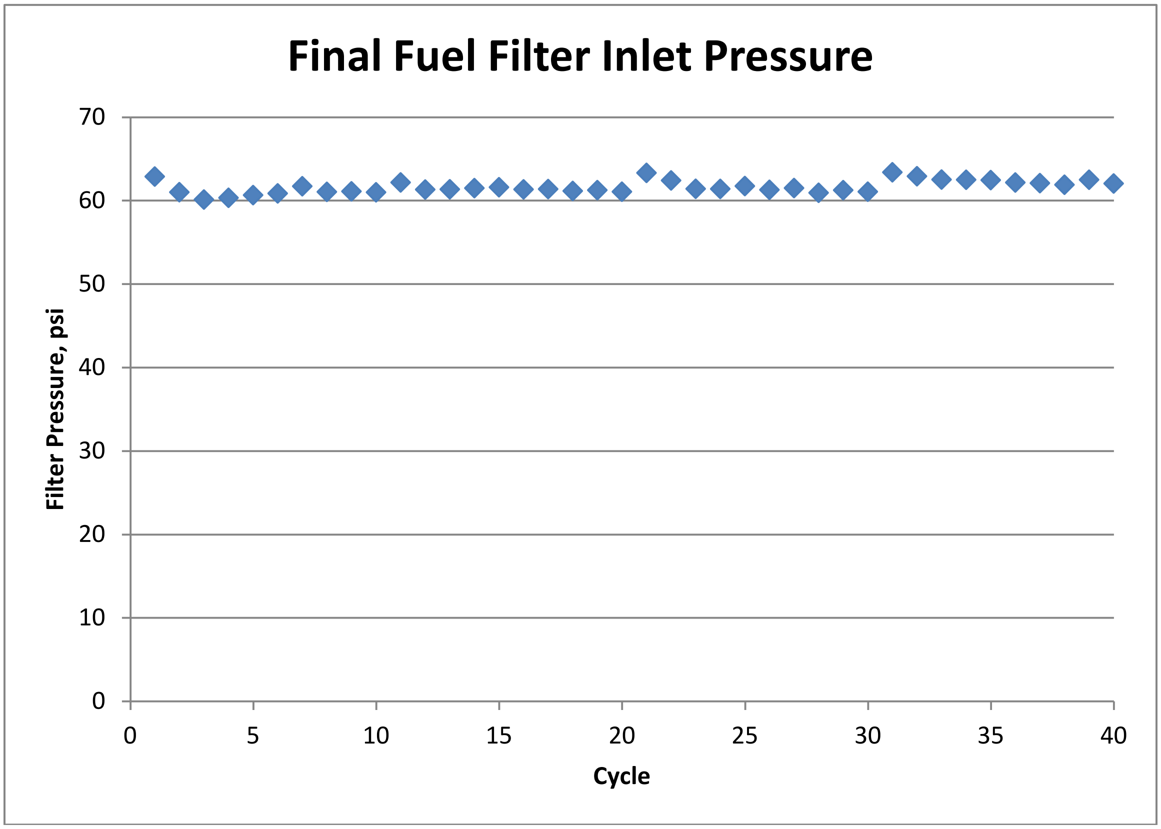

Figure F-6. Fuel Filter Pressure

Table F-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.8	1.2	69.8	81.8
Bypass Fuel Temperature, deg C	81.6	1.7	68.3	83.1
Rail Pressure, psi	19575	42	19426	19727
Injected Flow Rate, mL/min	1169.4	22.8	1053.8	1270.8
Return Fuel Flow Rate, mL/min	2490.8	60.1	2346.2	2602.6
Fuel Filter Inlet Pressure, psi	61.1	0.8	59.8	63.5
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.9	0.9	70.3	81.3
Bypass Fuel Temperature, deg C	82.0	1.3	72.0	83.3
Rail Pressure, psi	19402	49	19246	19569
Injected Flow Rate, mL/min	1197.3	20.5	1111.9	1309.6
Return Fuel Flow Rate, mL/min	2544.9	35.2	2480.7	2640.8
Fuel Filter Inlet Pressure, psi	61.4	0.4	60.7	62.9
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.8	1.1	70.3	81.9
Bypass Fuel Temperature, deg C	81.4	1.5	70.6	83.0
Rail Pressure, psi	19391	53	19231	19598
Injected Flow Rate, mL/min	1207.0	20.6	1127.3	1315.5
Return Fuel Flow Rate, mL/min	2582.6	25.8	2508.9	2637.1
Fuel Filter Inlet Pressure, psi	61.6	0.7	60.4	63.6
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	79.8	1.1	69.8	81.1
Bypass Fuel Temperature, deg C	81.2	1.6	68.7	83.2
Rail Pressure, psi	19566	42	19433	19727
Injected Flow Rate, mL/min	1196.1	21.4	1097.0	1298.8
Return Fuel Flow Rate, mL/min	2641.8	20.5	2567.3	2675.0
Fuel Filter Inlet Pressure, psi	62.5	0.5	61.6	64.1

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures F-7 and F-8.

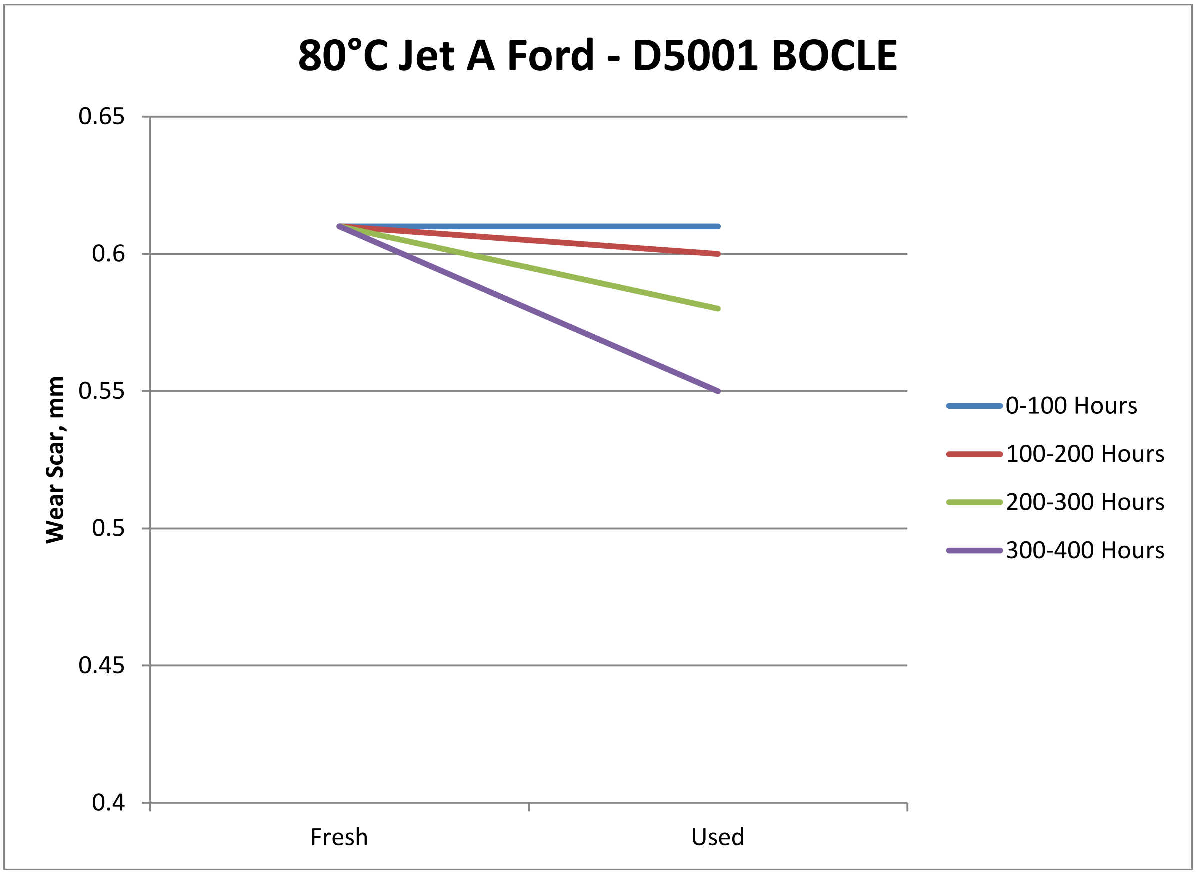

Figure F-7. ASTM D5001 BOCLE

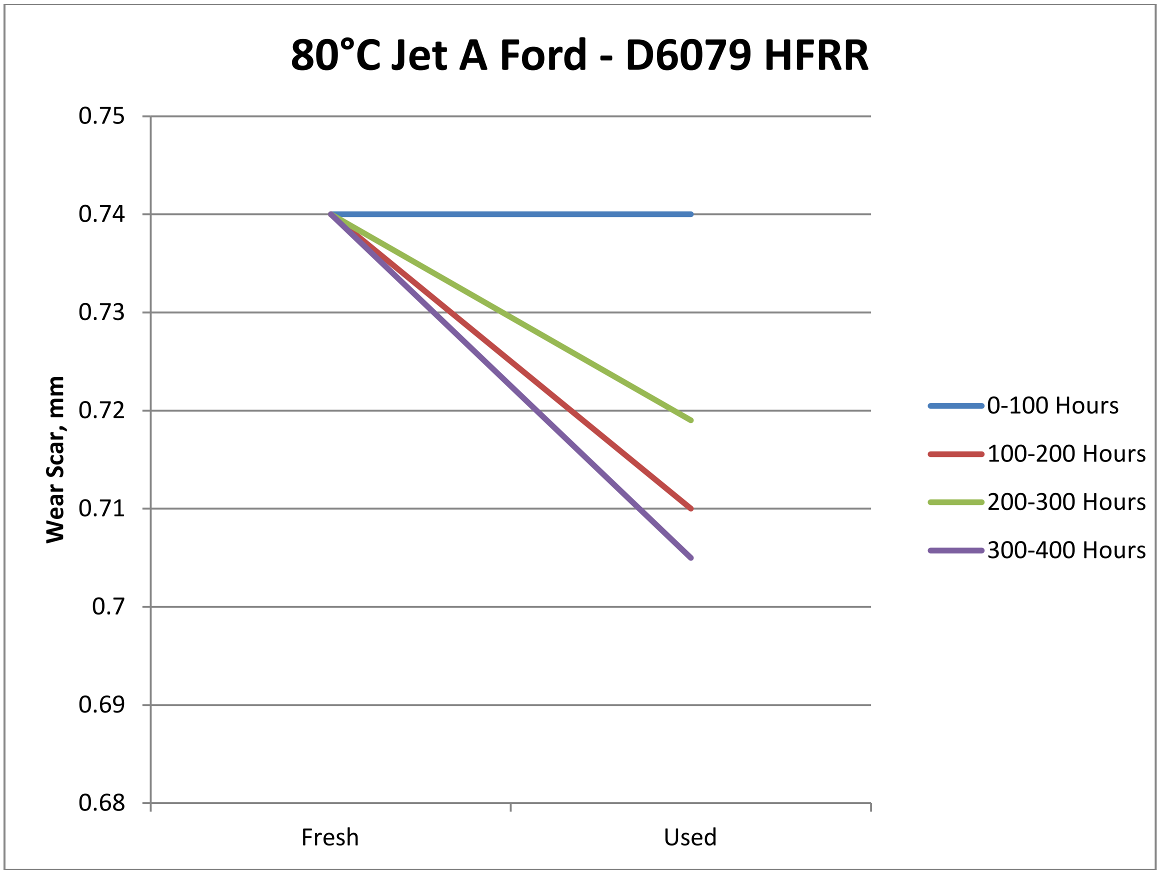

Figure F-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on Jet A at 80°C inlet temperature.

Fuel Pump

Figure F-9. Front Pump Bushing at 100 Hours

Figure F-10. Front Pump Bushing at 200 Hours

Figure F-11. Front Pump Bushing at 300 Hours

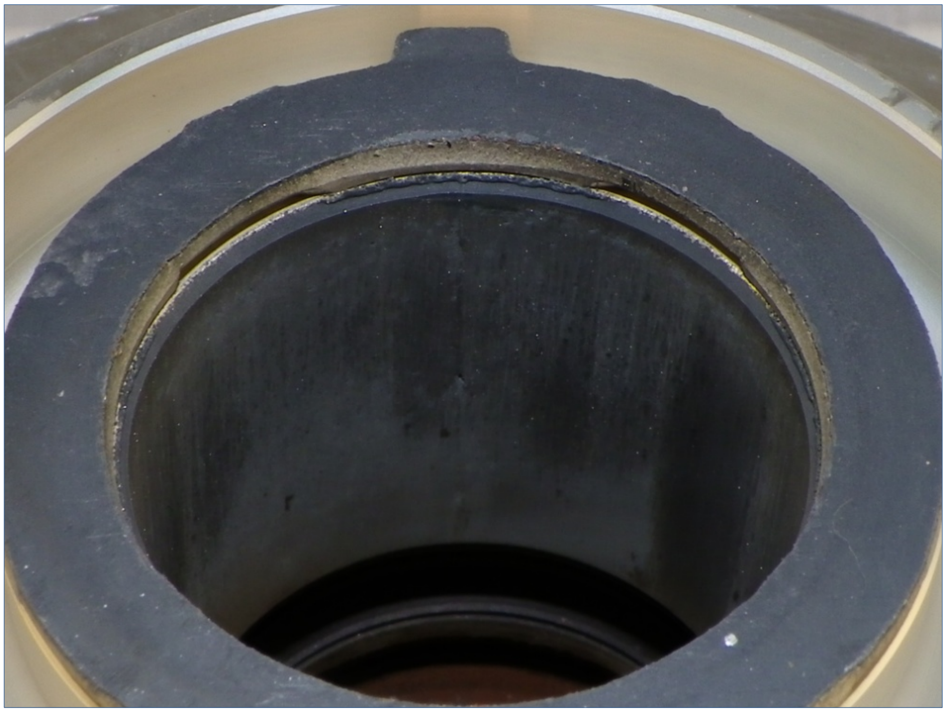

Figure F-12. Front Pump Bushing at 400 Hours

Figure F-13. Rear Pump Bushing

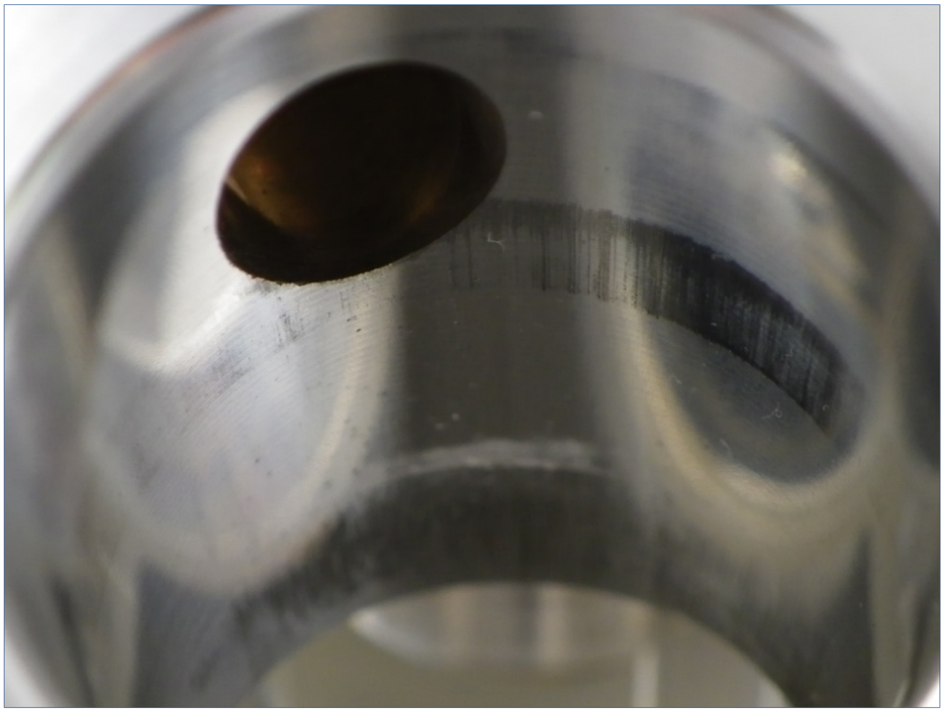

Figure F-14. Left Pump Bore Side 1 Upper

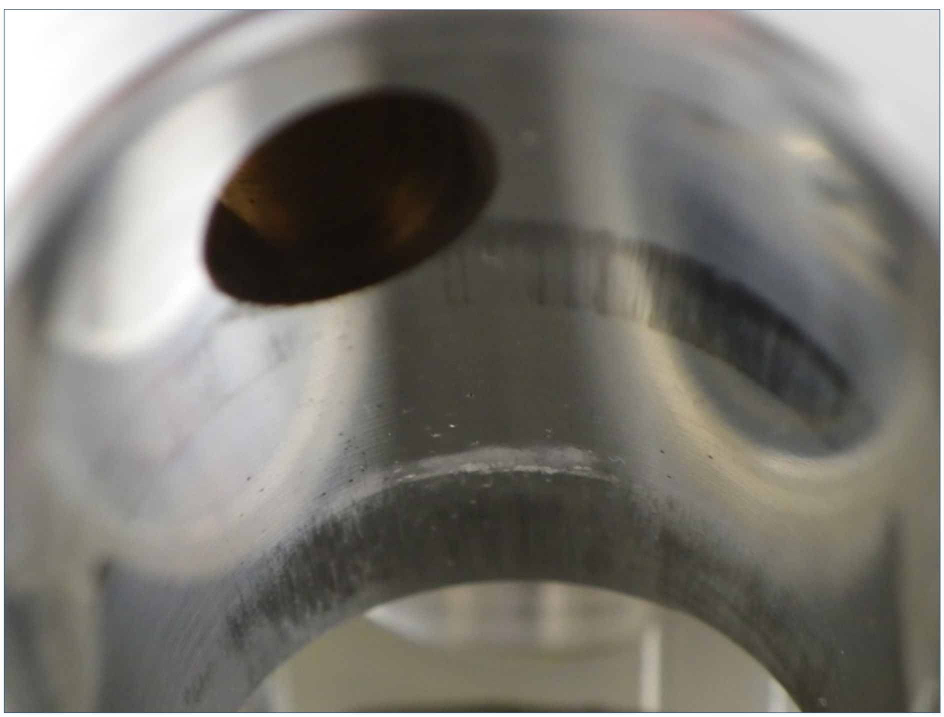

Figure F-15. Left Pump Bore Side 1 Lower

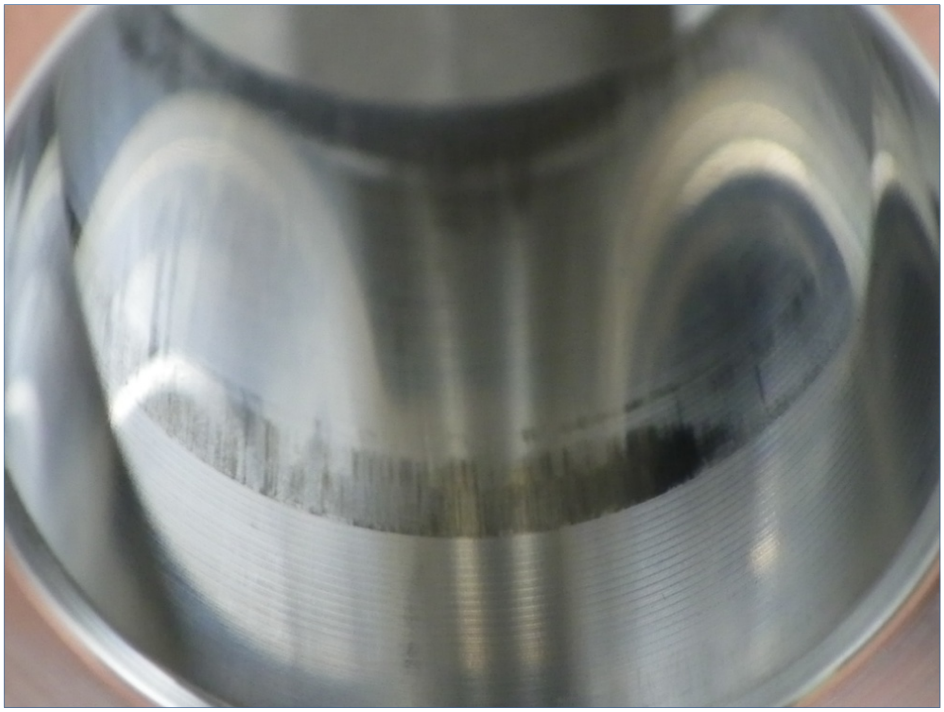

Figure F-16. Left Pump Bore Side 2

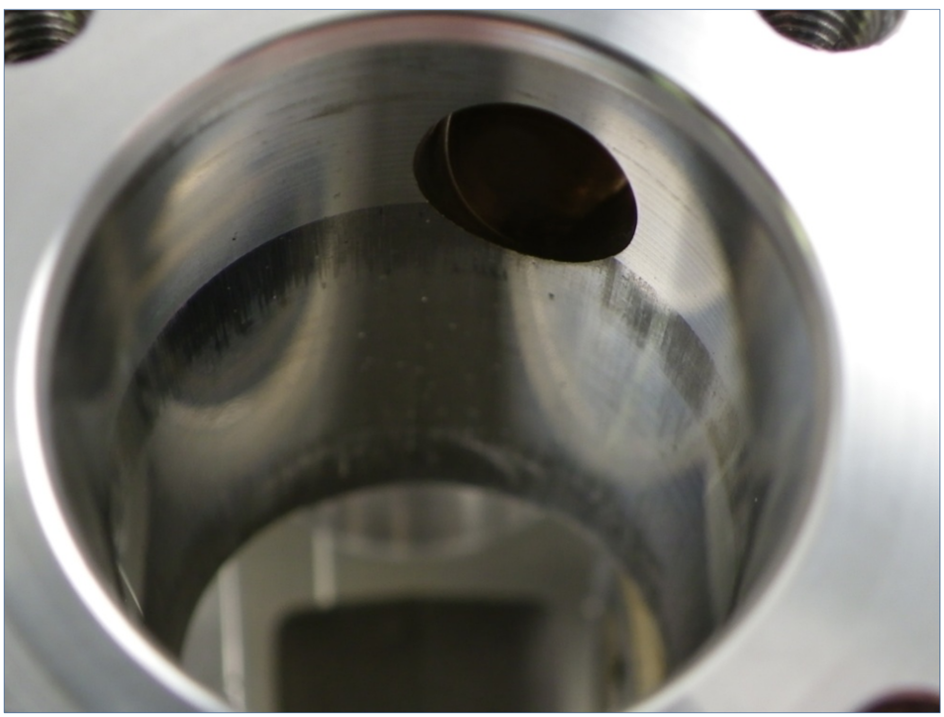

Figure F-17. Right Pump Bore Side 1

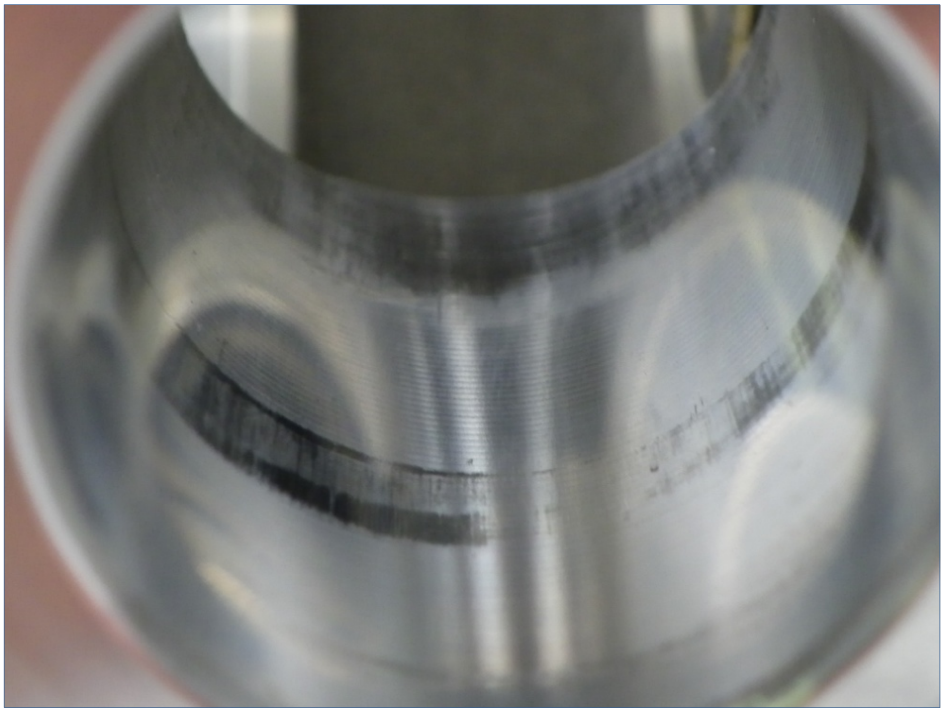

Figure F-18. Right Pump Bore Side 2

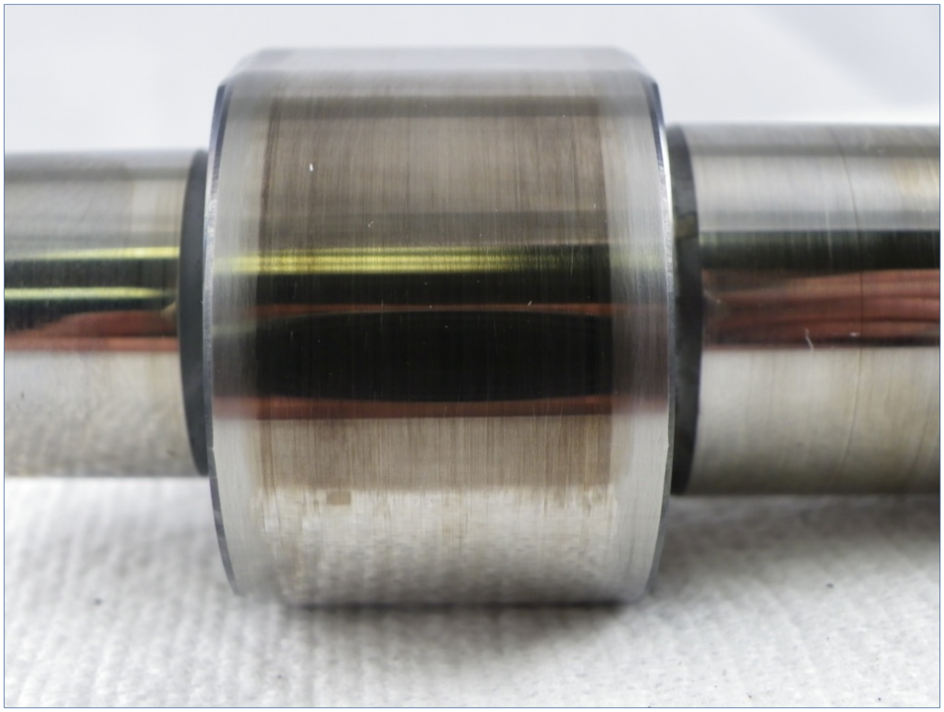

Figure F-19. Camshaft Lobe

Fuel Injector

Figure F-20. Injector Needle

Figure F-21. Upper Hydraulic Coupler Piston Side A

Figure F-22. Upper Hydraulic Coupler Piston Side B

Figure F-23. Lower Hydraulic Coupler Piston Side A

Figure F-24. Lower Hydraulic Coupler Piston Side B

Figure F-25. Intermediate Plate (Top)

Figure F-26. Intermediate Plate (Bottom)

Figure F-27. Control Valve Plate (Top)

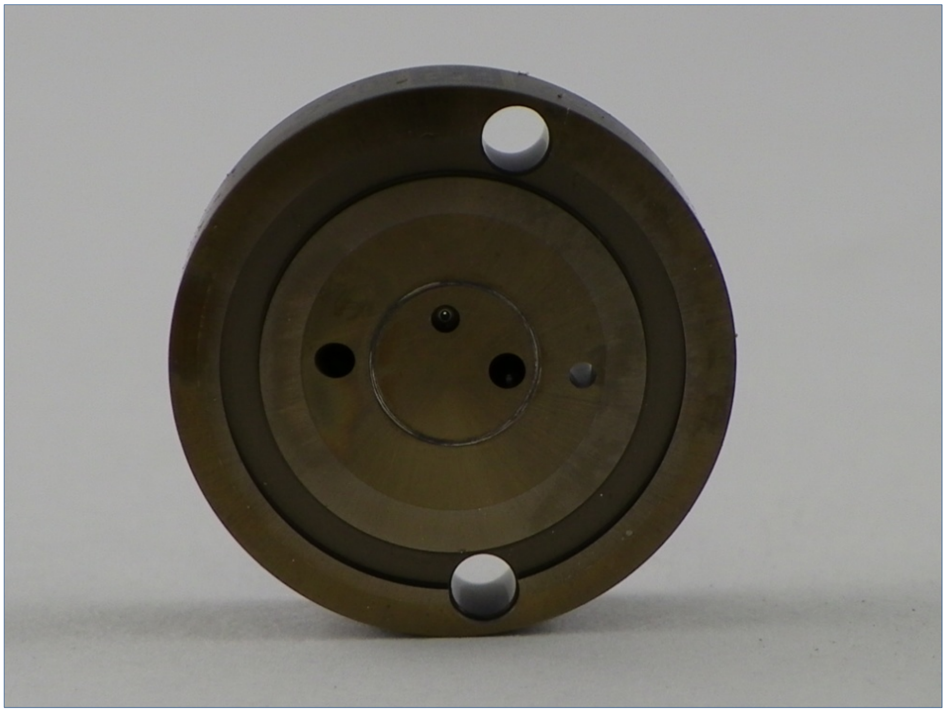

Figure F-28. Control Valve Plate (Bottom)

Figure F-29. Fuel Injector Control Valve

APPENDIX G

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Ford 6.7L Fuel System

Jet A (50%) and FT SPK (50%) Blend with 9 ppm DCI-4A

Blend-AF7824-60°C-FRD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Ford 6.7L Fuel System

Test Fuel: Jet A (50%) and FT SPK (50%) Blend with 9 ppm DCI-4A

Test Number: Blend-AF7824-60°C-FRD

Start of Test Date: January 10, 2012

End of Test Date: February 6, 2012

Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC

Force Projection Technologies

Warren, Michigan

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) conducted a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal was to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI) DCI-4A at a rate of 9 ppm, and a 1:1 blend of Jet A and the synthetic fuel with the CI/LI at rates of 9 ppm and 22.5 ppm. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Five tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and two at 80°C (176 °F), for a total of seven tests. An eighth test was conducted to isolate fuel impact on two critical components. The lower temperature ULSD test was considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Ford 6.7L fuel system manufactured by Bosch. The fuel-lubricated high pressure pump allows the system to reach rail pressures of up to 20,000 psi. It is operated at the same rotational speed as the engine crankshaft for a rated condition of 2800 rpm. Within the pump, the camshaft drives two plungers, oriented in a “V” configuration, which pressurize the fuel entering the rail. Each plunger is driven by two lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure system consists of a lift pump and filter combination to remove large particles and water along with a high efficiency final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Ford 6.7L system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Ford supplied engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The pump consisted of two high strength rods which compressed fuel to reach the desired rail pressure. Fuel then flowed to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled to a consistent temperature, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Table G-1.

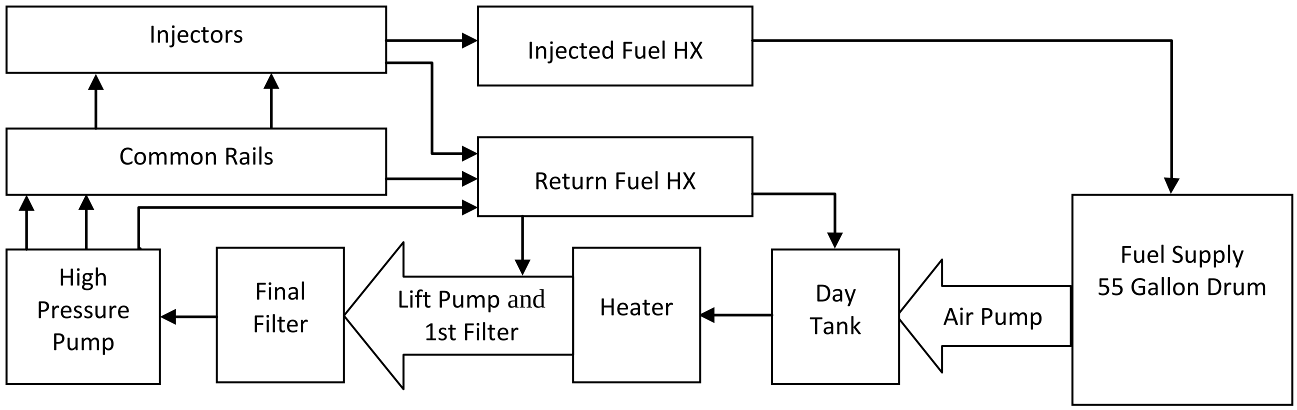

Figure G-1. Ford 6.7L Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table G-1.

Table G-1. NATO Cycle for Ford 6.7L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	600	0	0.5
2	2800	100	2
3	2940	0	0.5
4	2100	100	1
5*	600 to 2800	0 to 100	2
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2
10	1680	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Ford supplied ECM for monitoring purposes. Rail pressures were confirmed using the Ford service tool at various times throughout testing. The system did not experience any performance issues related to rail pressure during the course of the test, Figure G-2.

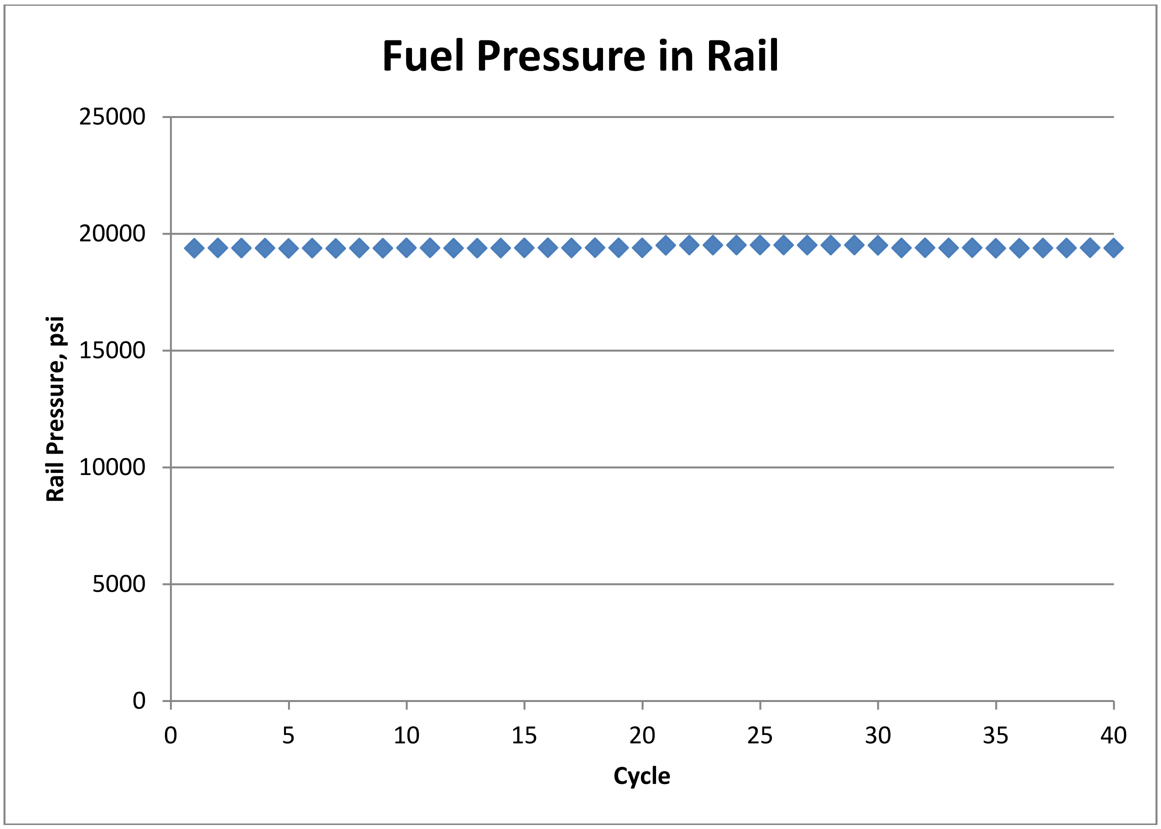

Figure G-2. Fuel Rail Pressure

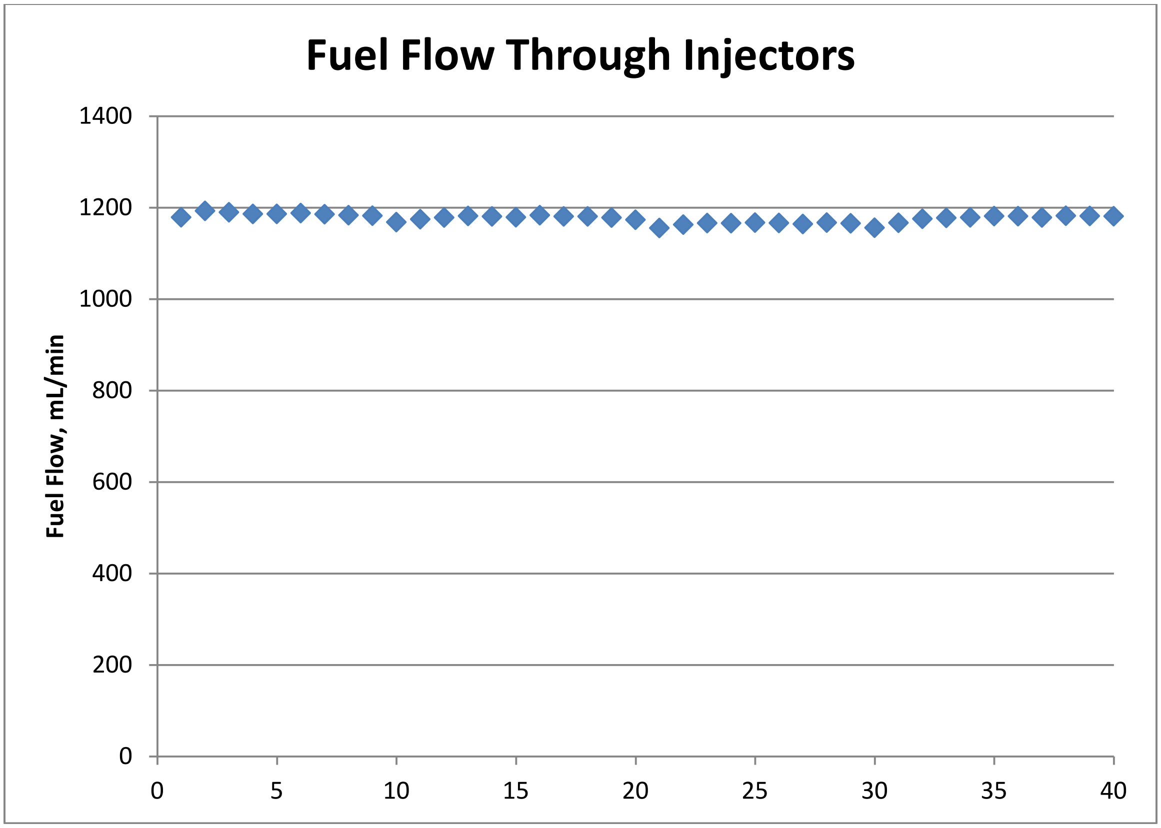

Figure G-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump volume control valve, rail protection check valve, and injector bypass/cooling flow. After an initial break-in period, there was a gradual increase in return fuel flow over the course of the test.

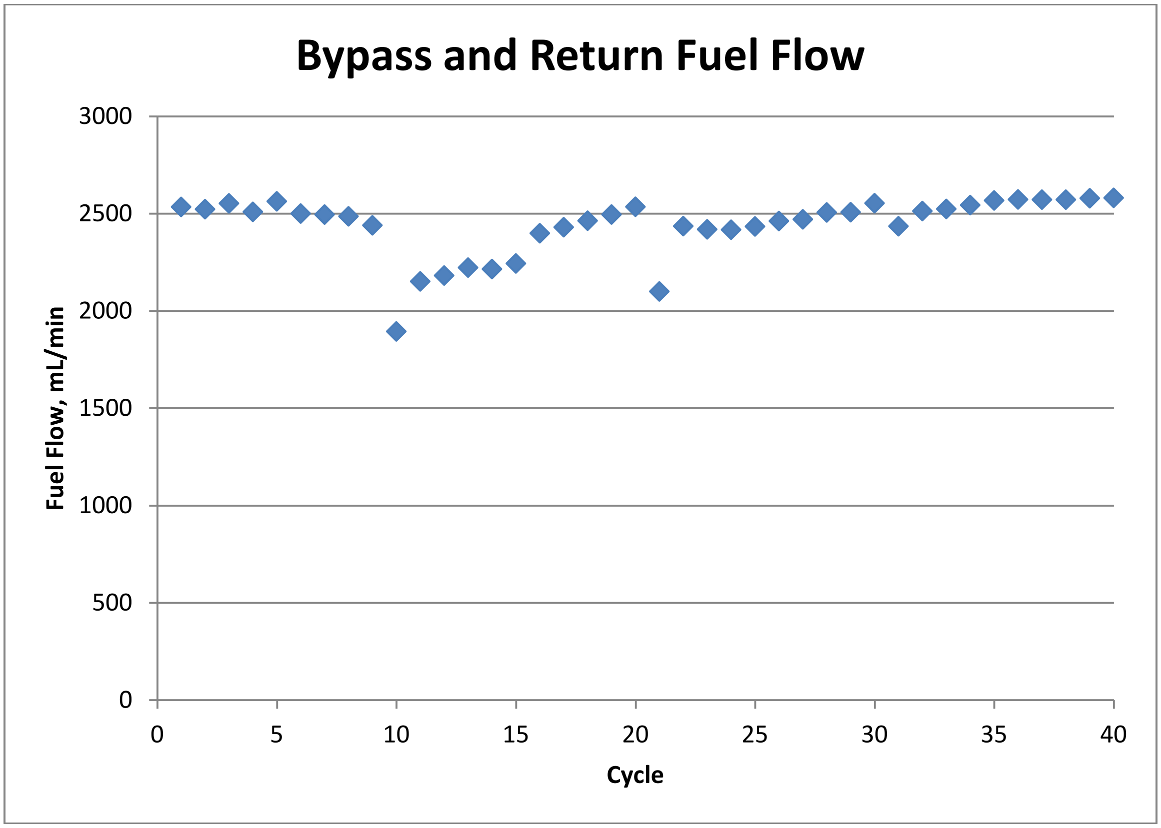

Figure G-4. Return Fuel Flow

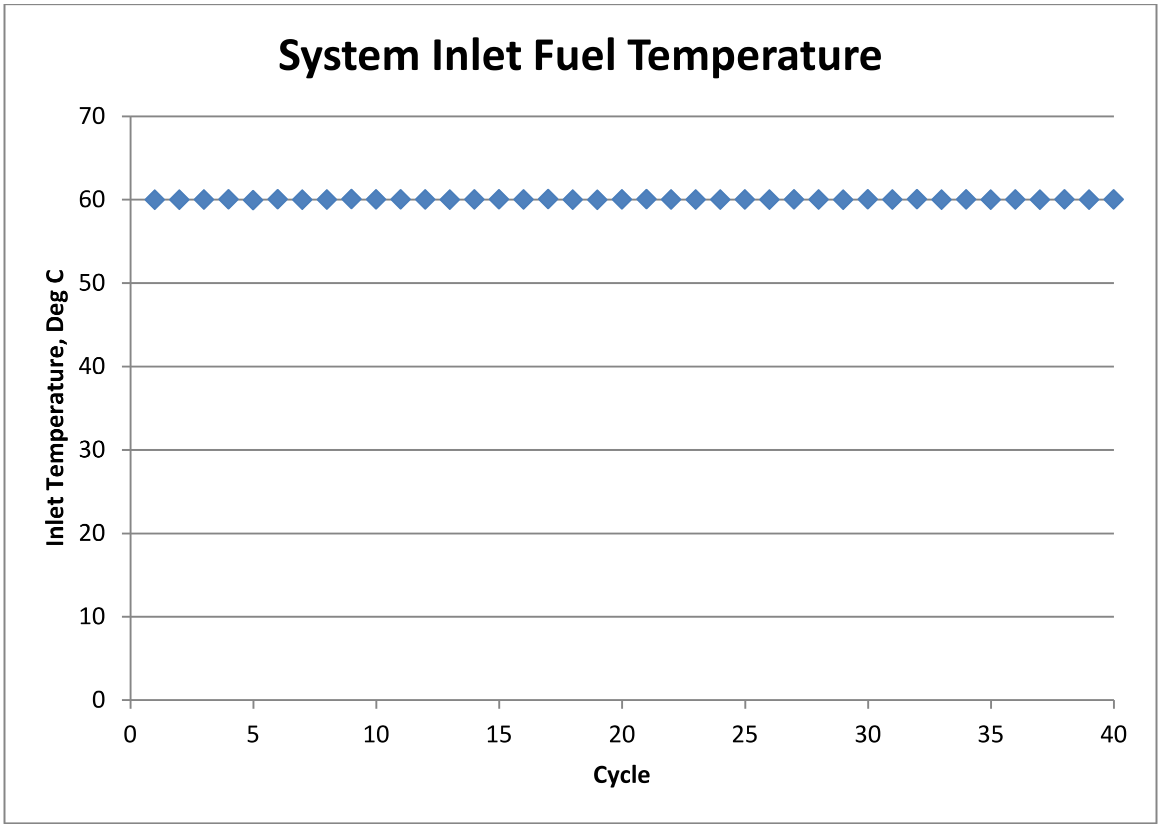

Figure G-5. System Inlet Fuel Temperature

Fuel filter inlet pressure is a measure of the pressure being developed by the lift pump and fuel/water separator unit of the system.

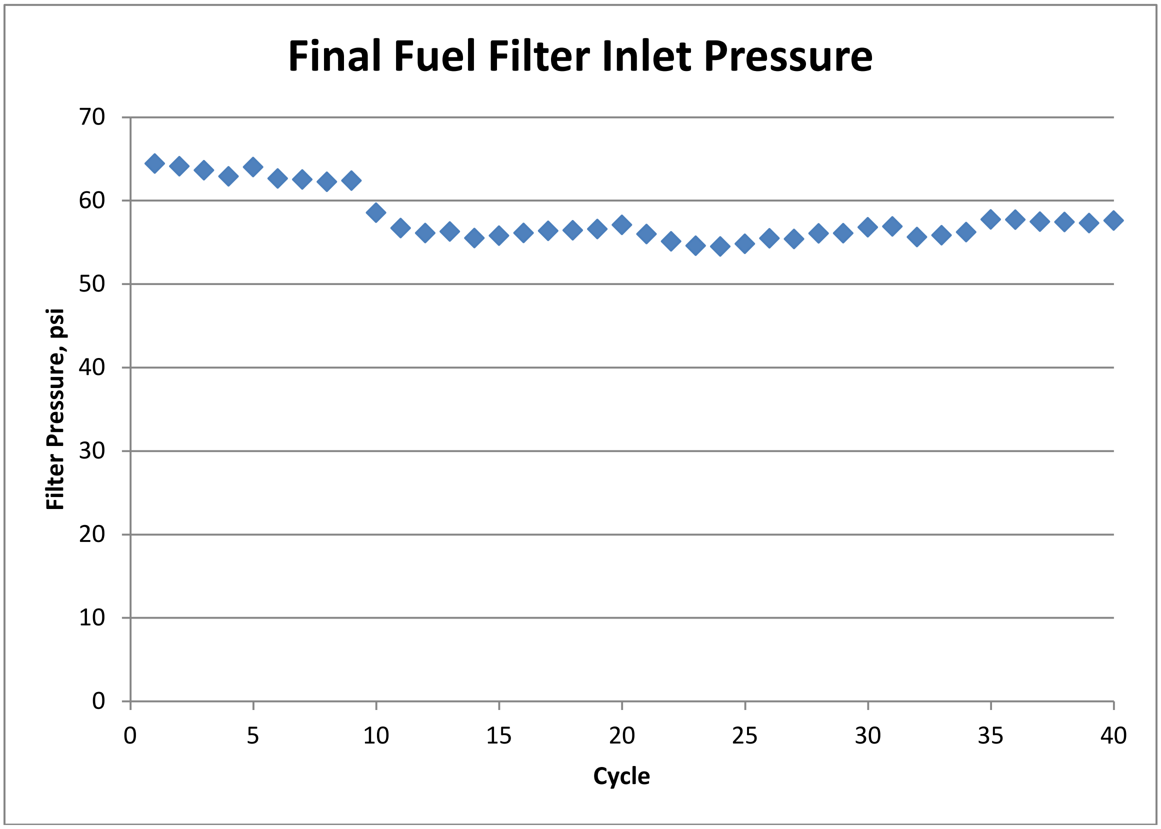

Figure G-6. Fuel Filter Pressure

Table G-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.4	56.9	62.9
Bypass Fuel Temperature, deg C	63.2	1.0	56.4	66.3
Rail Pressure, psi	19387	47	19238	19562
Injected Flow Rate, mL/min	1184.9	19.3	1105.5	1357.2
Return Fuel Flow Rate, mL/min	2450.4	190.8	1865.6	2604.0
Fuel Filter Inlet Pressure, psi	62.8	1.6	58.1	65.5
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.4	58.9	62.6
Bypass Fuel Temperature, deg C	65.7	0.5	61.2	67.1
Rail Pressure, psi	19397	41	19242	19536
Injected Flow Rate, mL/min	1180.1	14.9	1143.8	1261.3
Return Fuel Flow Rate, mL/min	2334.5	137.4	2122.5	2566.0
Fuel Filter Inlet Pressure, psi	56.3	0.5	55.1	57.6
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.4	58.9	62.3
Bypass Fuel Temperature, deg C	65.3	0.7	61.0	66.8
Rail Pressure, psi	19515	41	19360	19624
Injected Flow Rate, mL/min	1164.8	15.9	1126.1	1245.0
Return Fuel Flow Rate, mL/min	2431.4	117.6	2064.9	2567.3
Fuel Filter Inlet Pressure, psi	55.5	0.7	54.0	57.2
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.4	58.9	62.5
Bypass Fuel Temperature, deg C	64.9	0.6	60.7	66.4
Rail Pressure, psi	19395	44	19227	19521
Injected Flow Rate, mL/min	1179.7	13.8	1145.8	1260.0
Return Fuel Flow Rate, mL/min	2546.5	43.7	2385.7	2594.3
Fuel Filter Inlet Pressure, psi	57.0	0.8	55.3	58.1

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures G-7 and G-8.

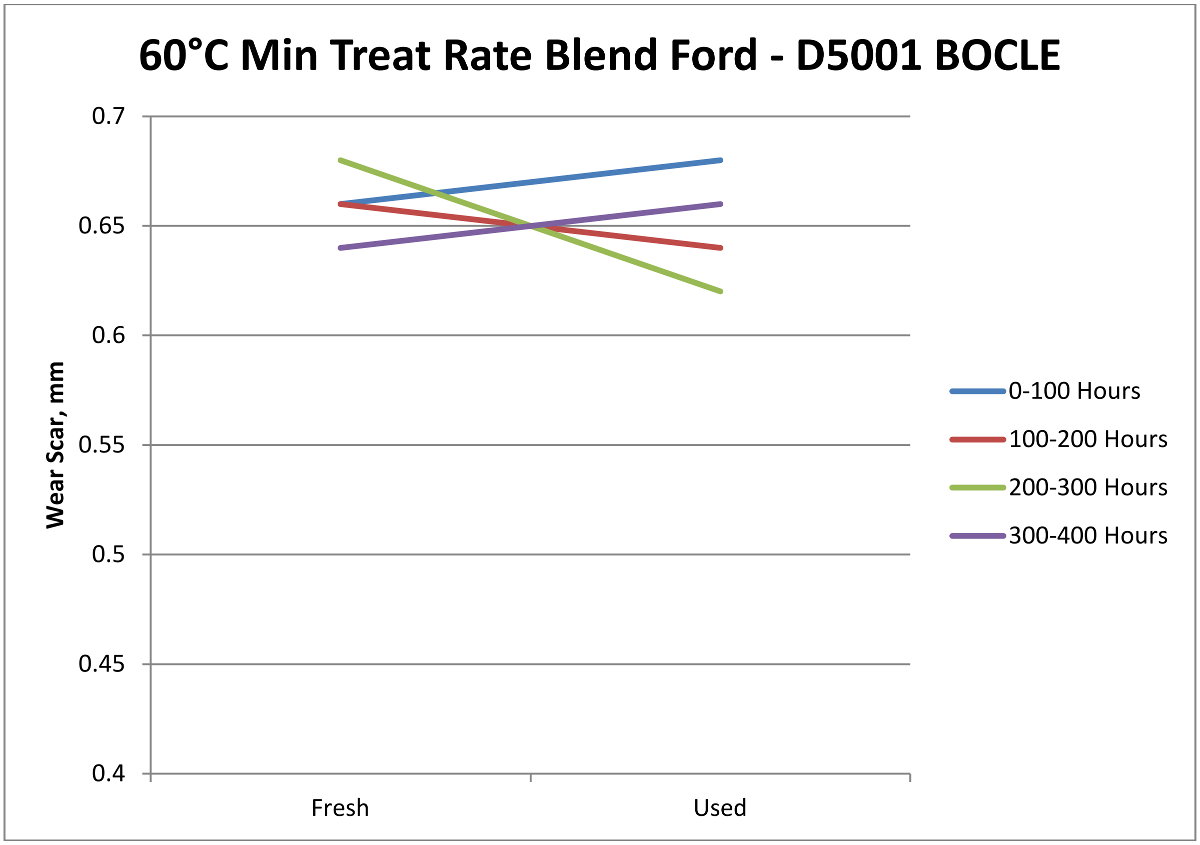

Figure G-7. ASTM D5001 BOCLE

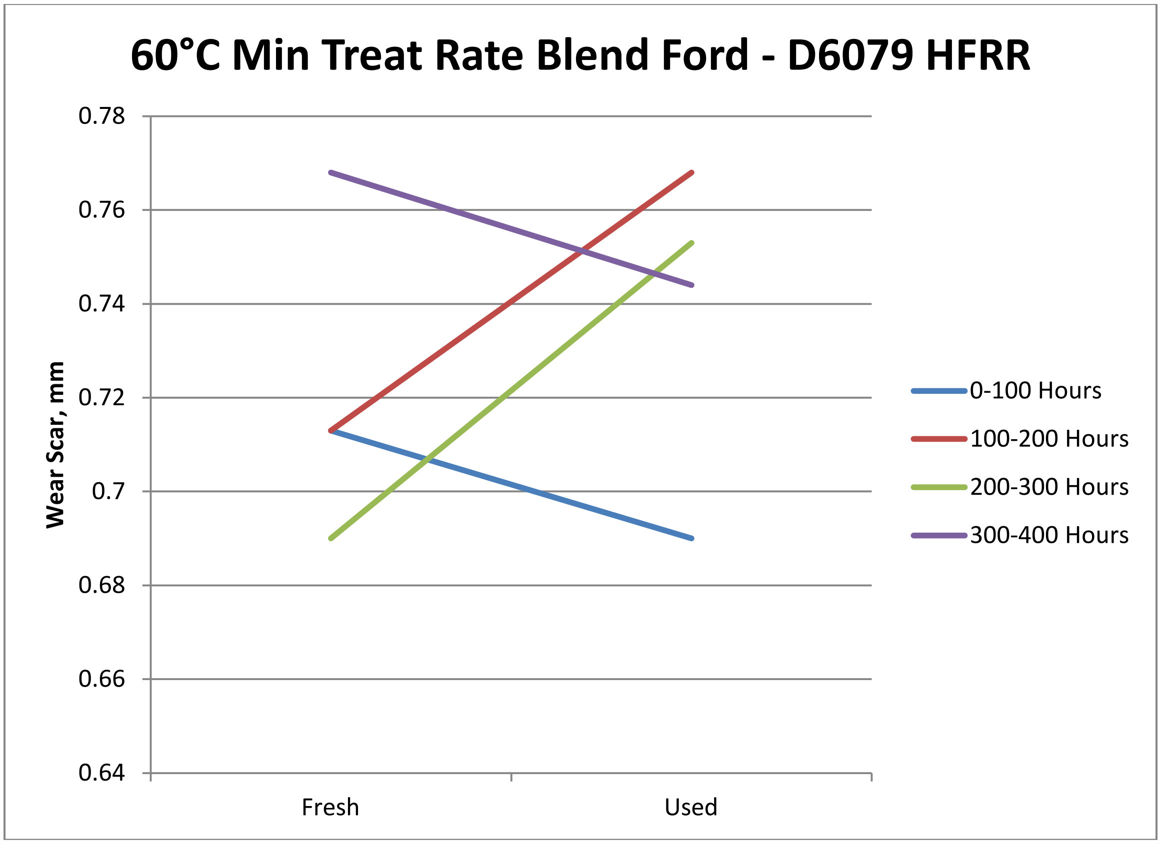

Figure G-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on a Blend of the SPK fuel and Jet A, all treated with 9 ppm DCI-4A at 60°C inlet temperature.

Fuel Pump

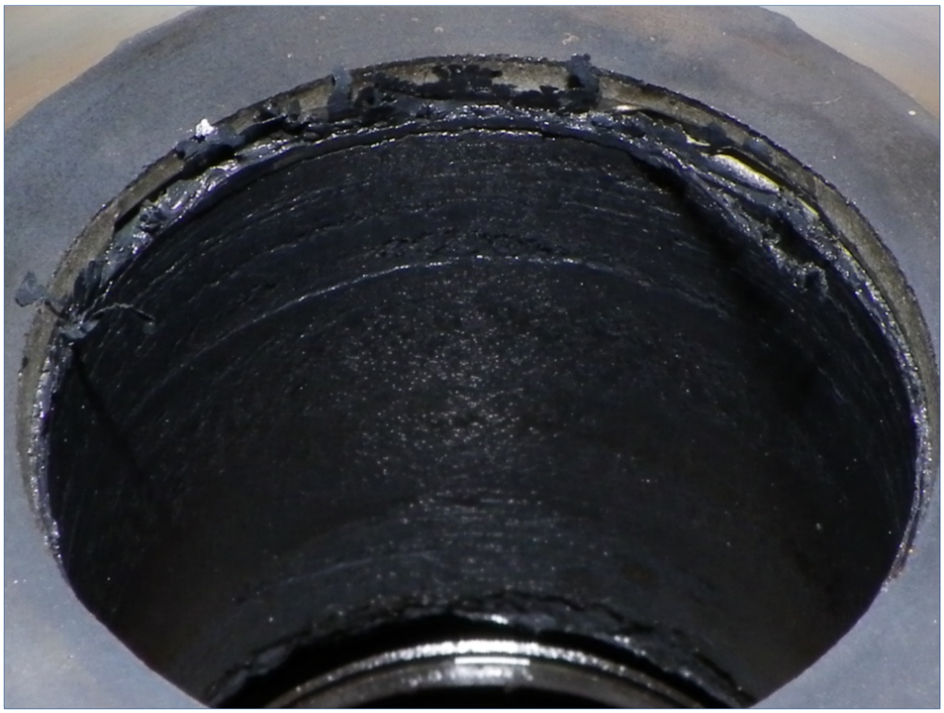

Figure G-9. Front Pump Bushing at 100 Hours

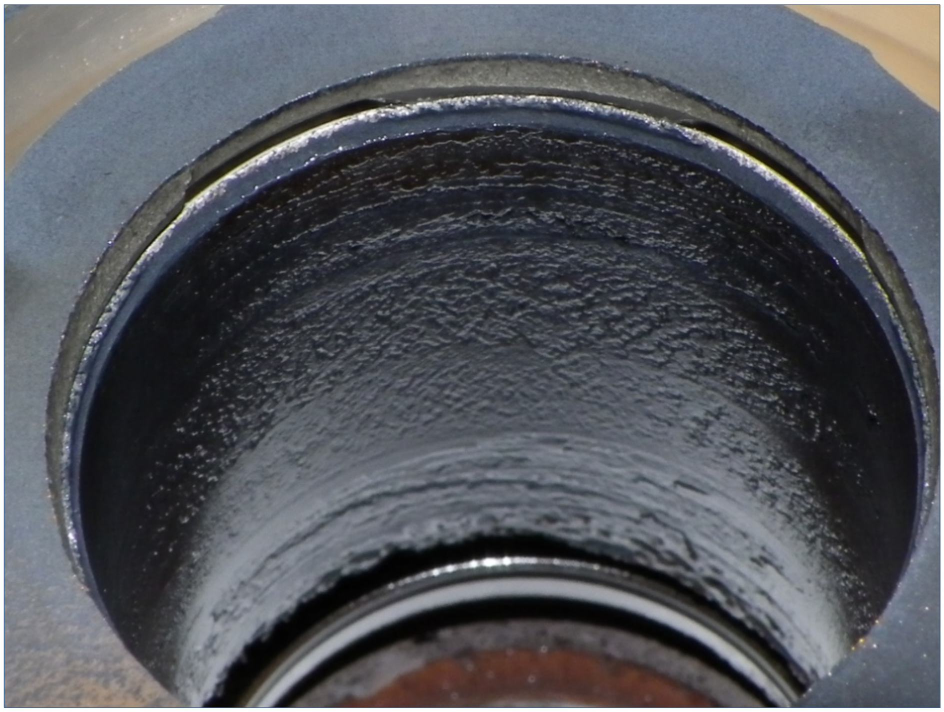

Figure G-10. Front Pump Bushing at 200 Hours

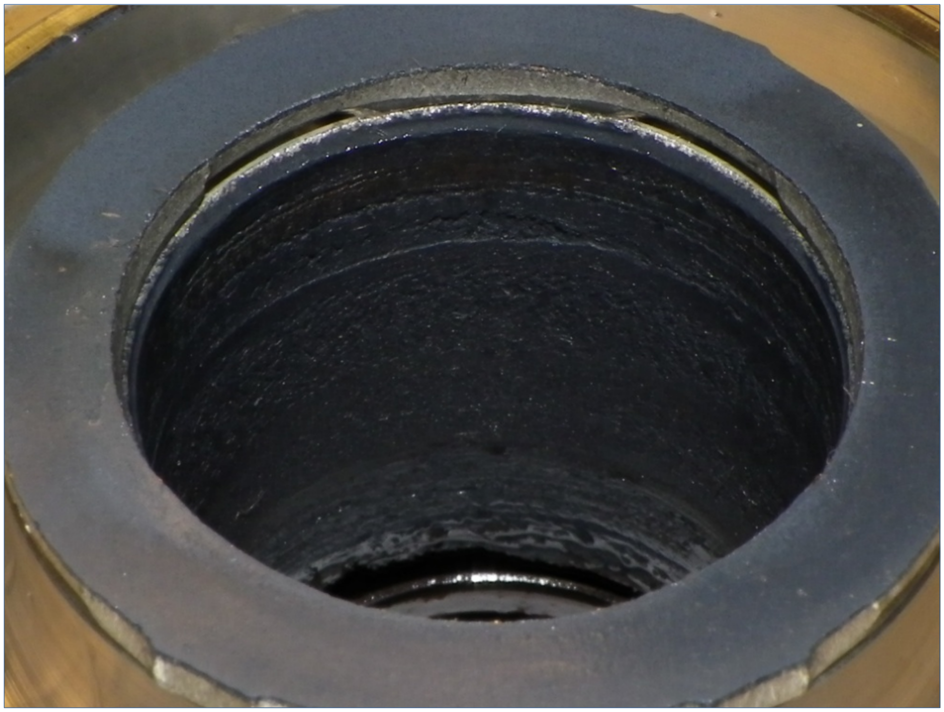

Figure G-11. Front Pump Bushing at 300 Hours

Figure G-12. Front Pump Bushing at 400 Hours

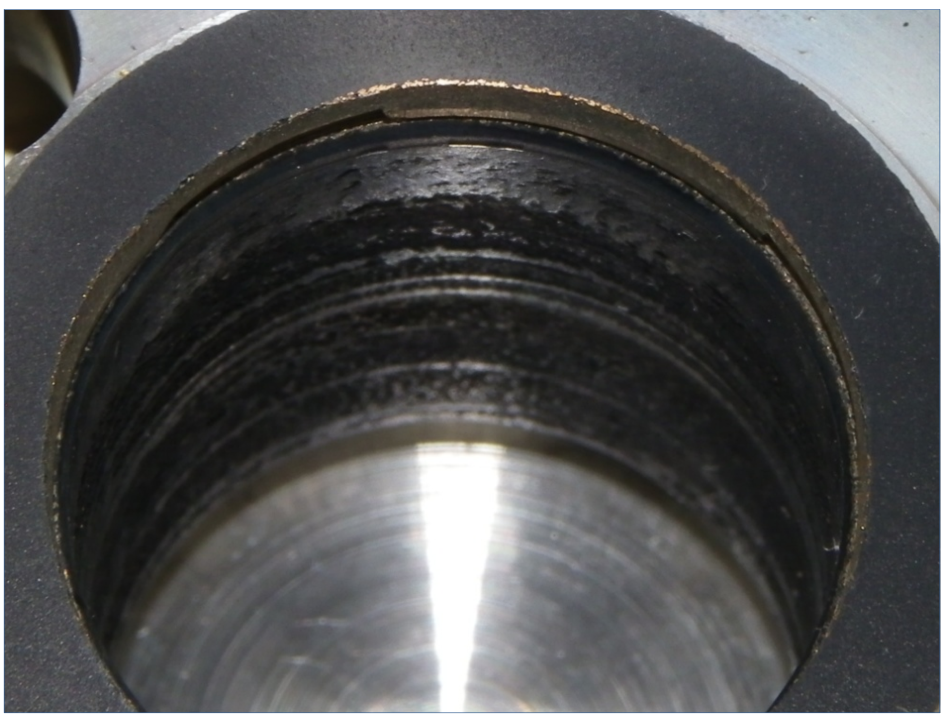

Figure G-13. Rear Pump Bushing

Figure G-14. Left Pump Bore

Figure G-15. Right Pump Bore

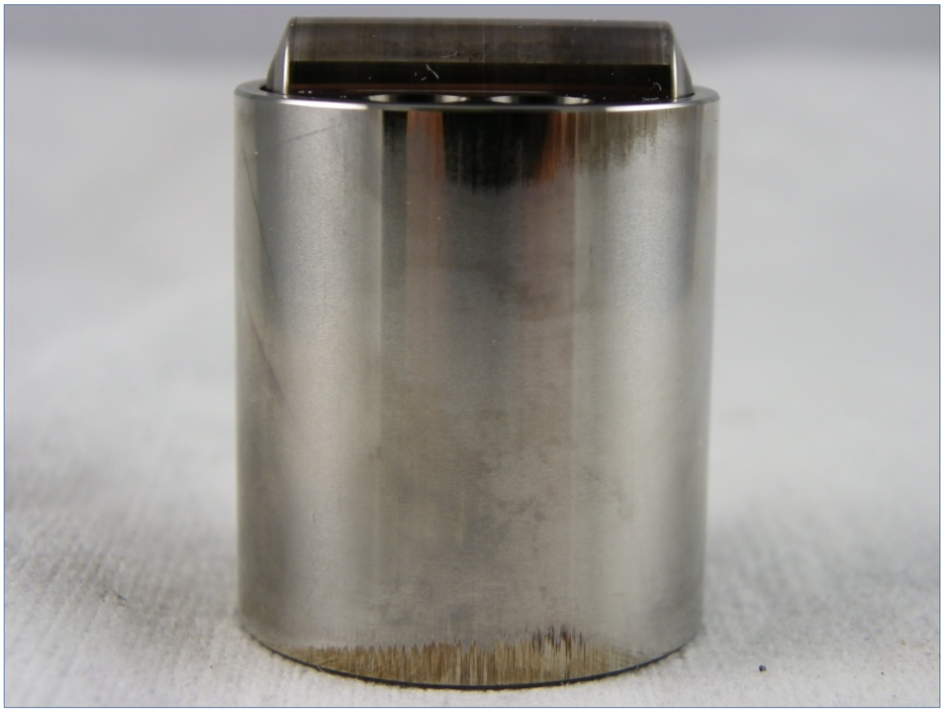

Figure G-16. Left Cam Follower Side 1

Figure G-17. Left Cam Follower Side 2

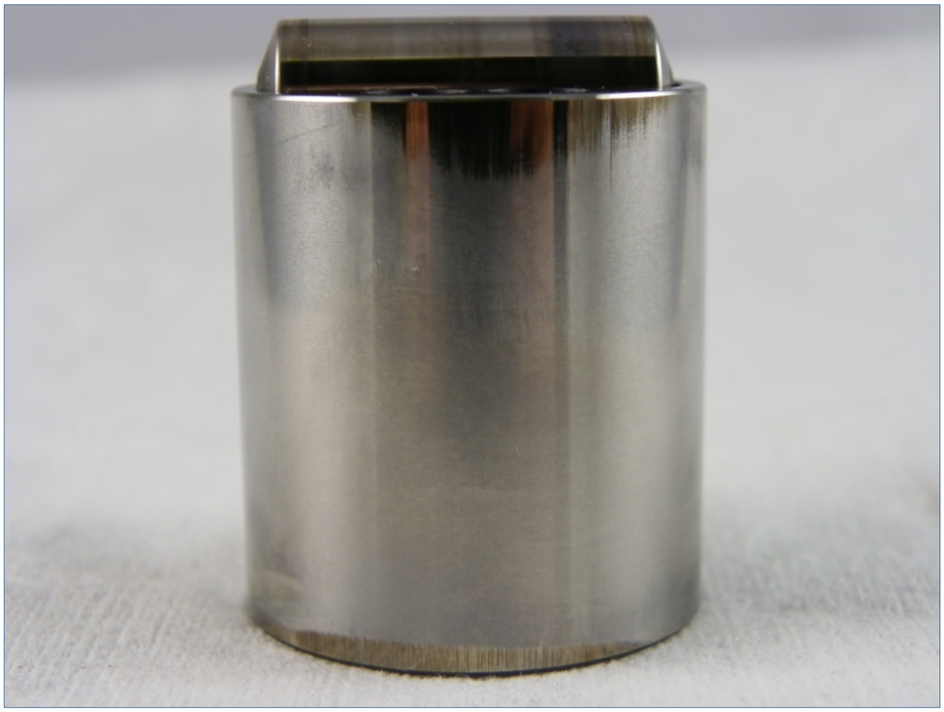

Figure G-18. Right Cam Follower Side 1

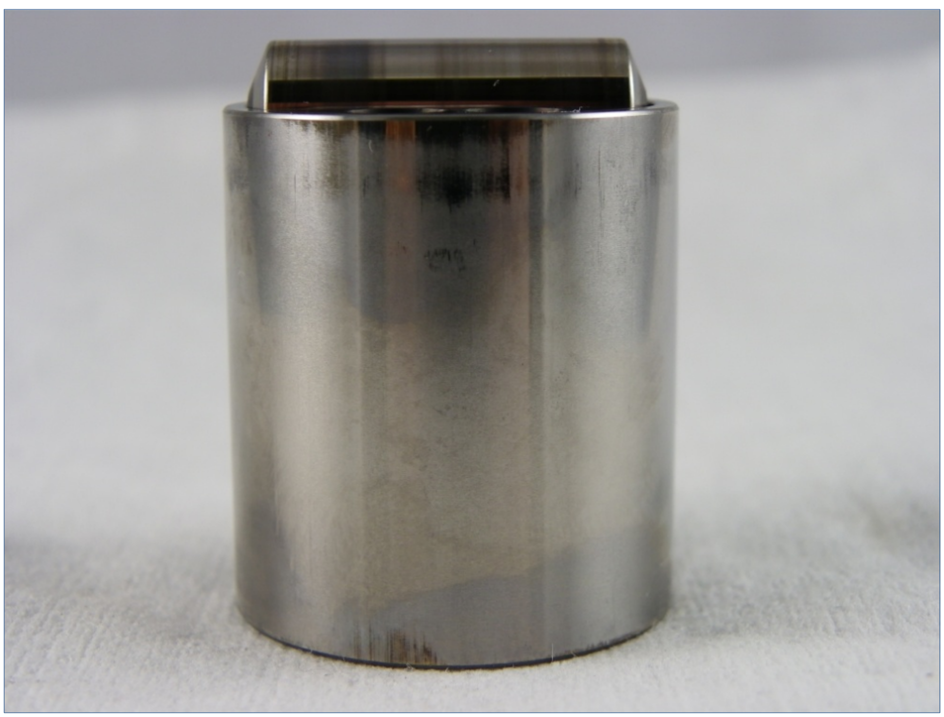

Figure G-19. Right Cam Follower Side 2

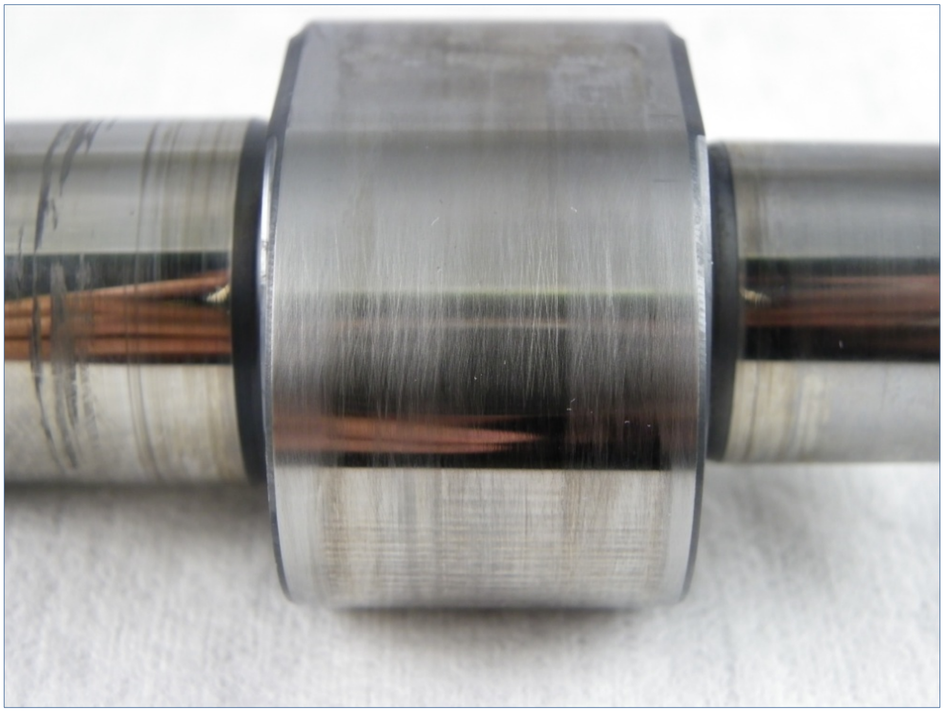

Figure G-20. Camshaft Lobe

Fuel Injector

Figure G-21. Injector Needle

Figure G-22. Upper Hydraulic Coupler Piston Side A

Figure G-23. Upper Hydraulic Coupler Piston Side B

Figure G-24. Lower Hydraulic Coupler Piston Side A

Figure G-25. Lower Hydraulic Coupler Piston Side B

Figure G-26. Intermediate Plate (Top)

Figure G-27. Intermediate Plate (Bottom)

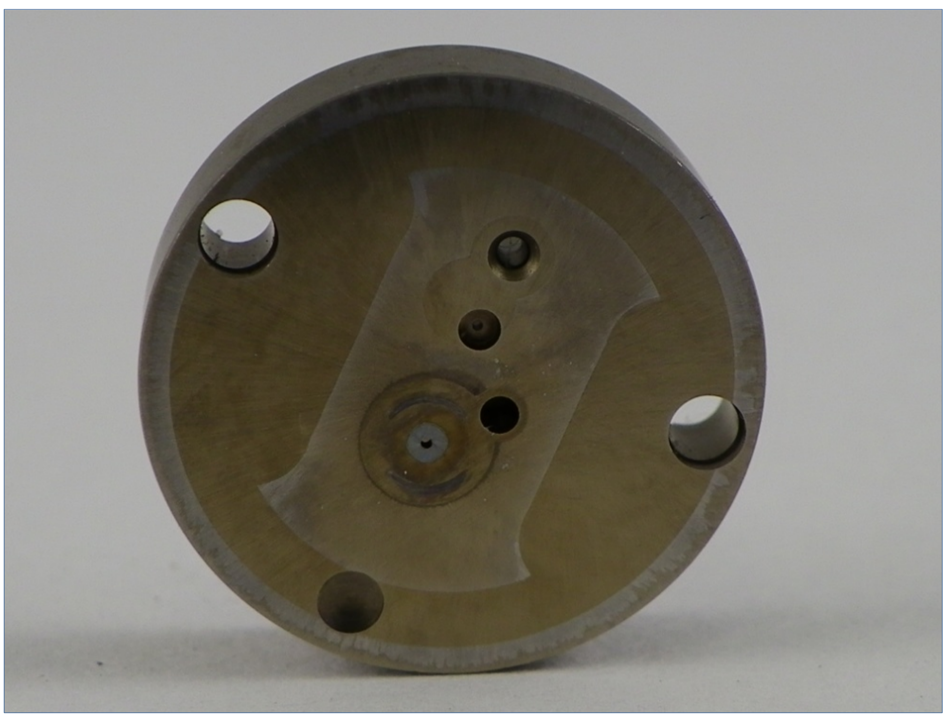

Figure G-28. Control Valve Plate (Top)

Figure G-29. Control Valve Plate (Bottom)

APPENDIX H

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Ford 6.7L Fuel System

Jet A (50%) and FT SPK (50%) Blend with 22.5 ppm DCI-4A

Max-Blend–60°C-FRD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Ford 6.7L Fuel System

Test Fuel: Jet A (50%) and FT SPK (50%) Blend with 22.5 ppm DCI-4A

Test Number: Max-Blend–60°C-FRD

Start of Test Date: February 13, 2012

End of Test Date: March 8, 2012

Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC

Force Projection Technologies

Warren, Michigan

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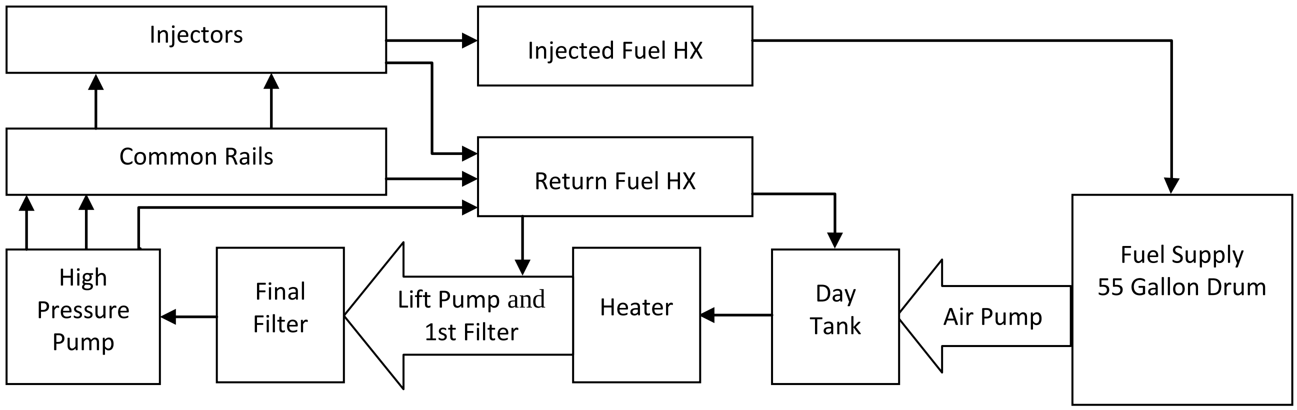

Figure H-1. Ford 6.7L Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table H-1.

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5*	600 to 2800	0 to 100	2
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2
10	1680	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Ford supplied ECM for monitoring purposes. Rail pressures were confirmed using the Ford service tool at various times throughout testing. The system did not experience any performance issues related to rail pressure during the course of the test, Figure H-2.

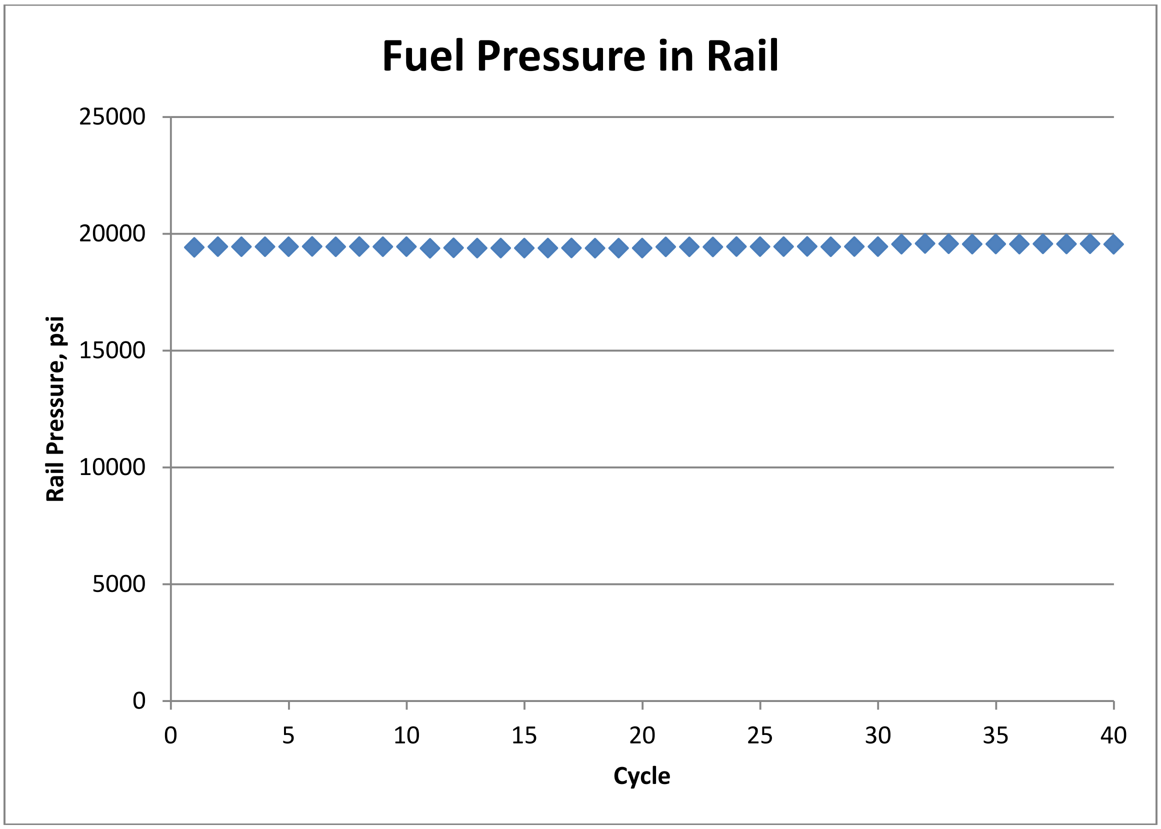

Figure H-2. Fuel Rail Pressure

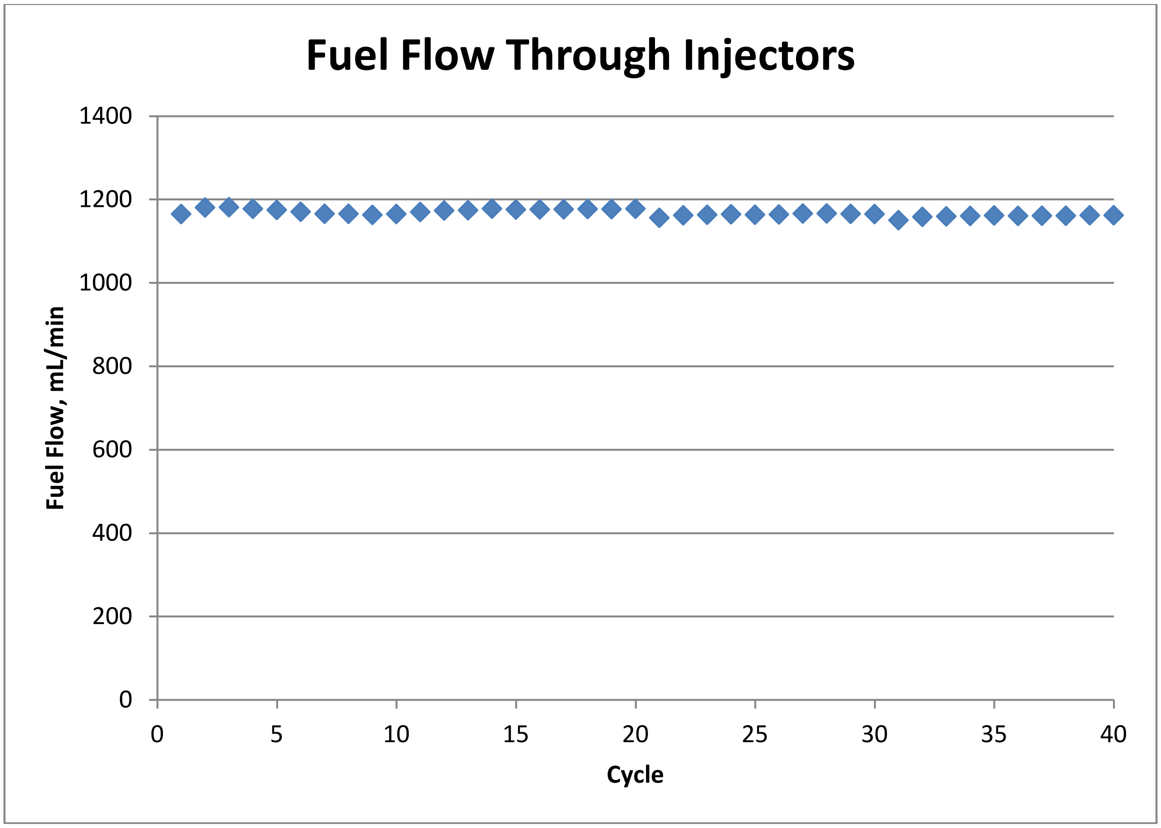

Figure H-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump volume control valve, rail protection check valve, and injector bypass/cooling flow.

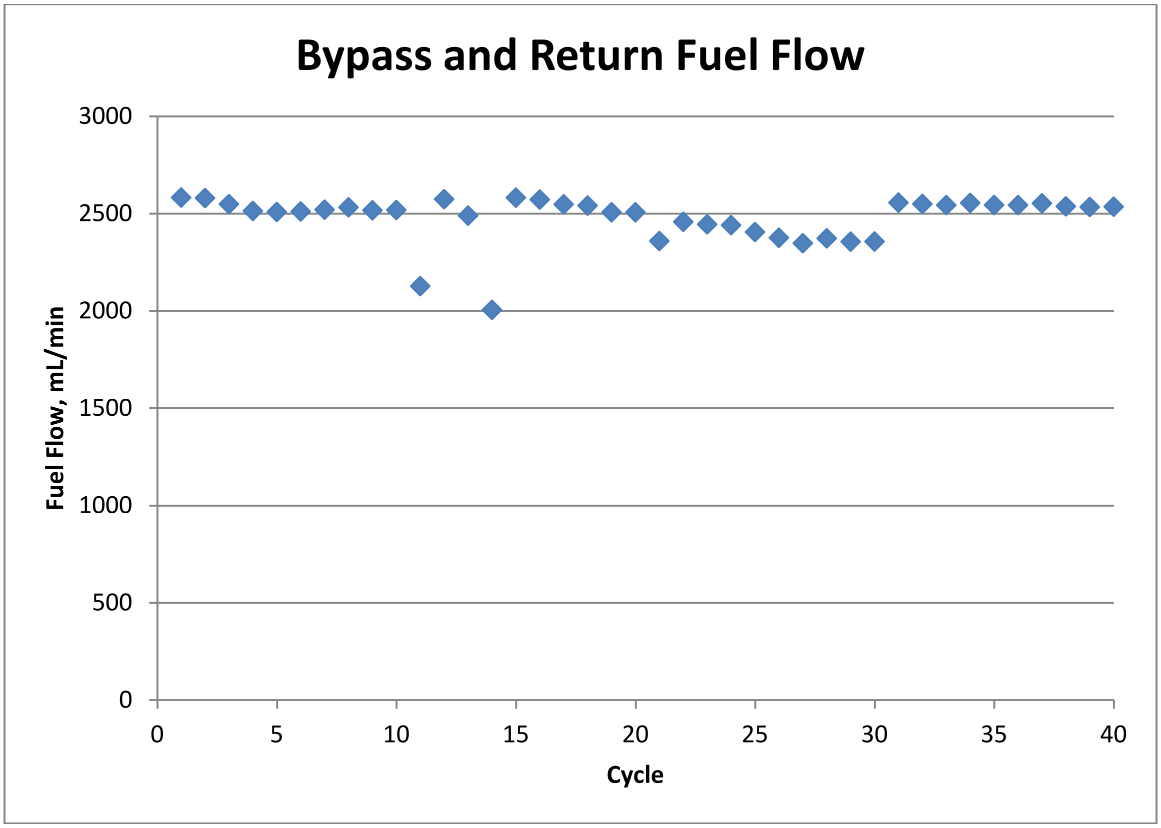

Figure H-4. Return Fuel Flow

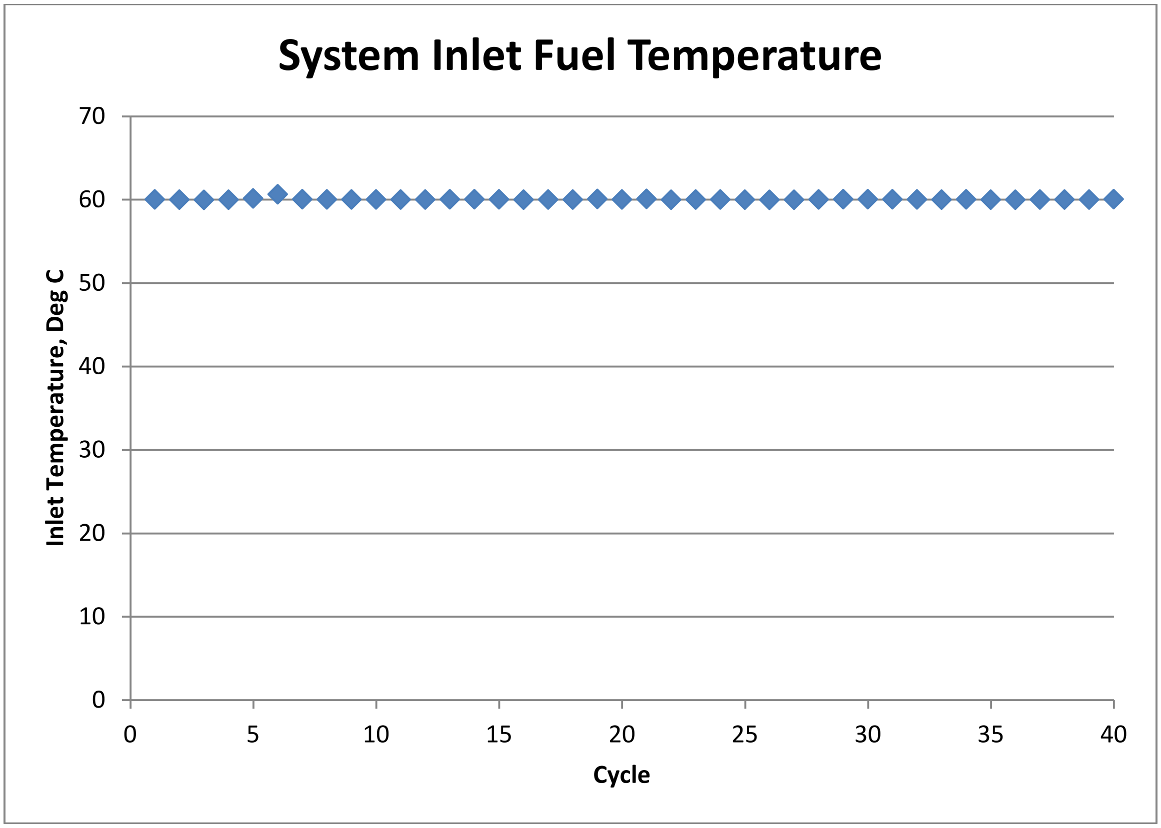

Figure H-5. System Inlet Fuel Temperature

Fuel filter inlet pressure is a measure of the pressure being developed by the lift pump and fuel/water separator unit of the system.

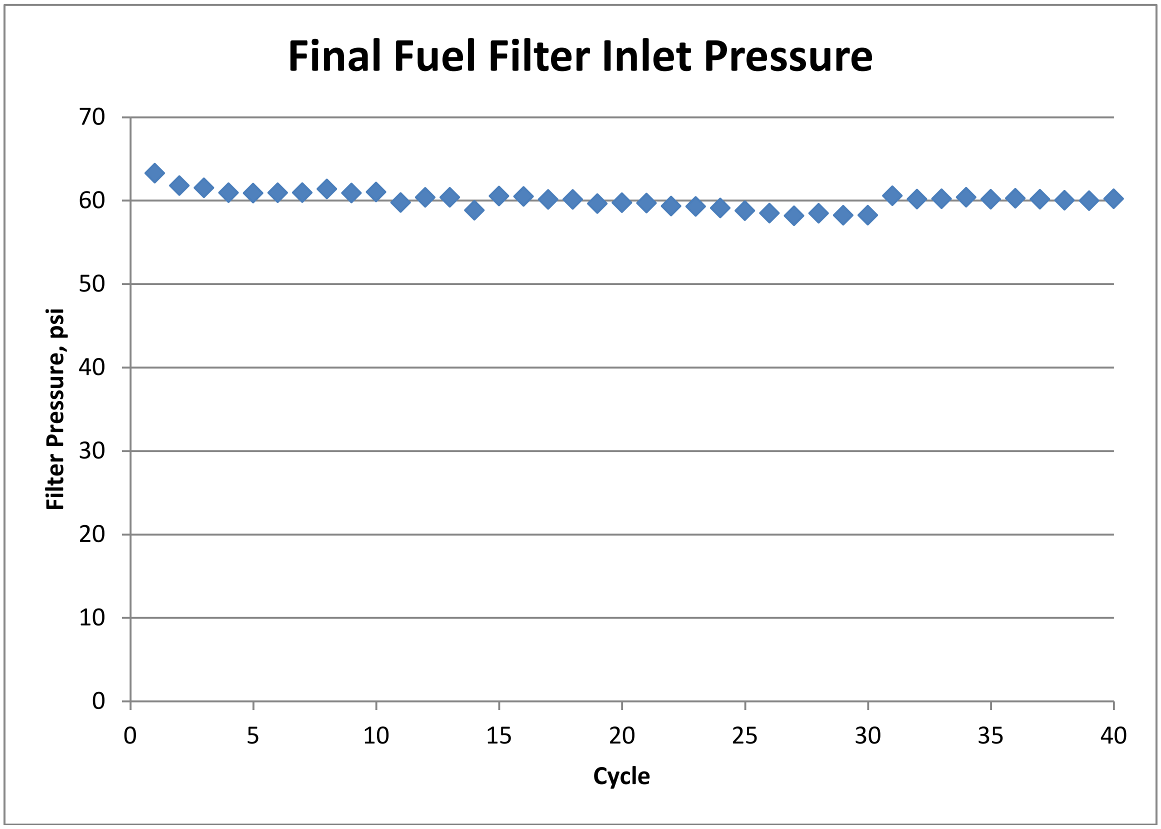

Figure H-6. Fuel Filter Pressure

Table H-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.5	58.9	63.5
Bypass Fuel Temperature, deg C	67.8	0.7	64.8	75.0
Rail Pressure, psi	19448	52	19301	19617
Injected Flow Rate, mL/min	1172.2	15.5	1099.1	1291.1
Return Fuel Flow Rate, mL/min	2533.2	28.3	2469.0	2605.4
Fuel Filter Inlet Pressure, psi	61.4	0.7	60.5	64.4
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.5	59.0	63.9
Bypass Fuel Temperature, deg C	66.1	0.6	63.2	67.7
Rail Pressure, psi	19389	46	19220	19529
Injected Flow Rate, mL/min	1176.9	13.5	1148.7	1261.5
Return Fuel Flow Rate, mL/min	2445.8	193.7	1975.8	2605.0
Fuel Filter Inlet Pressure, psi	60.0	0.5	58.5	60.8
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.4	58.9	63.2
Bypass Fuel Temperature, deg C	65.5	0.4	62.4	66.6
Rail Pressure, psi	19449	42	19308	19584
Injected Flow Rate, mL/min	1165.1	14.2	1138.9	1248.9
Return Fuel Flow Rate, mL/min	2391.9	41.9	2298.2	2497.5
Fuel Filter Inlet Pressure, psi	58.8	0.5	57.9	60.3
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.1	0.4	59.2	63.2
Bypass Fuel Temperature, deg C	65.4	0.4	62.5	66.6
Rail Pressure, psi	19566	38	19440	19694
Injected Flow Rate, mL/min	1161.1	14.3	1132.7	1247.2
Return Fuel Flow Rate, mL/min	2545.3	12.4	2493.4	2585.9
Fuel Filter Inlet Pressure, psi	60.2	0.2	59.7	60.9

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures H-7 and H-8.

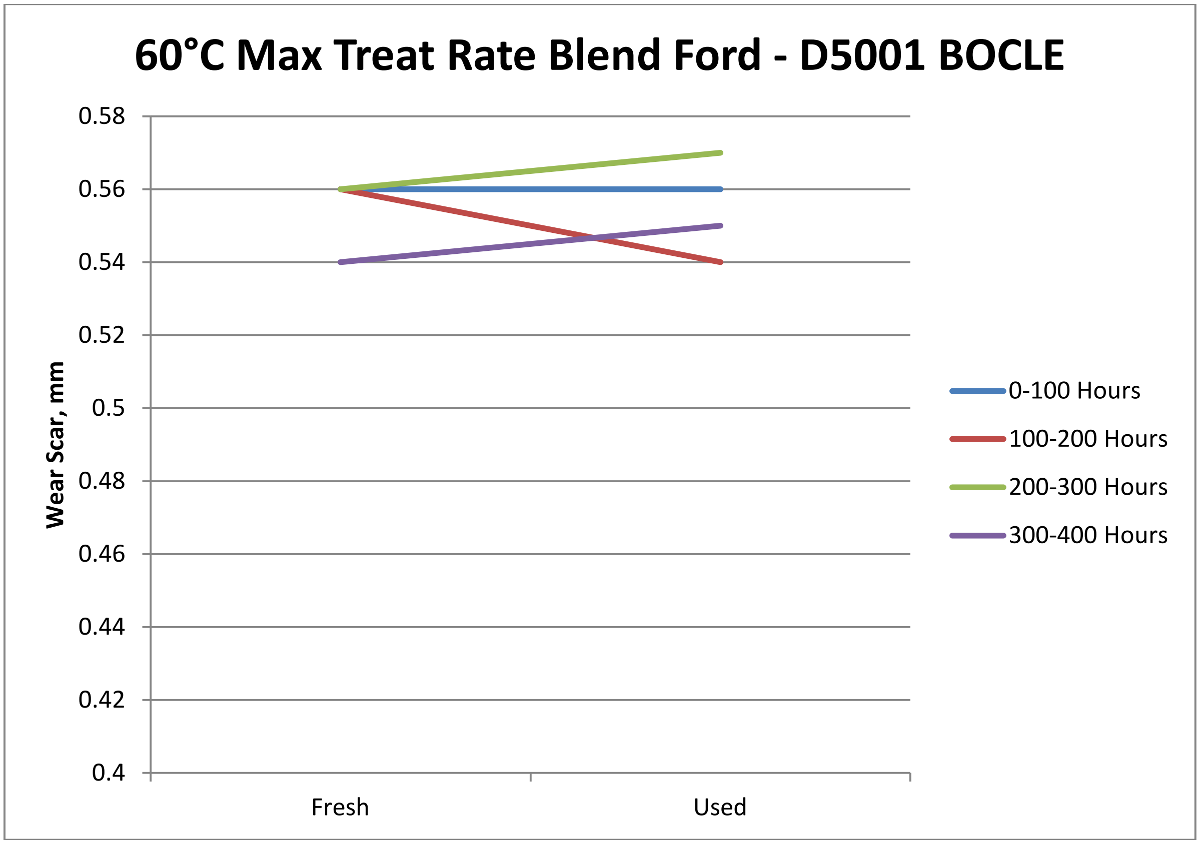

Figure H-7. ASTM D5001 BOCLE

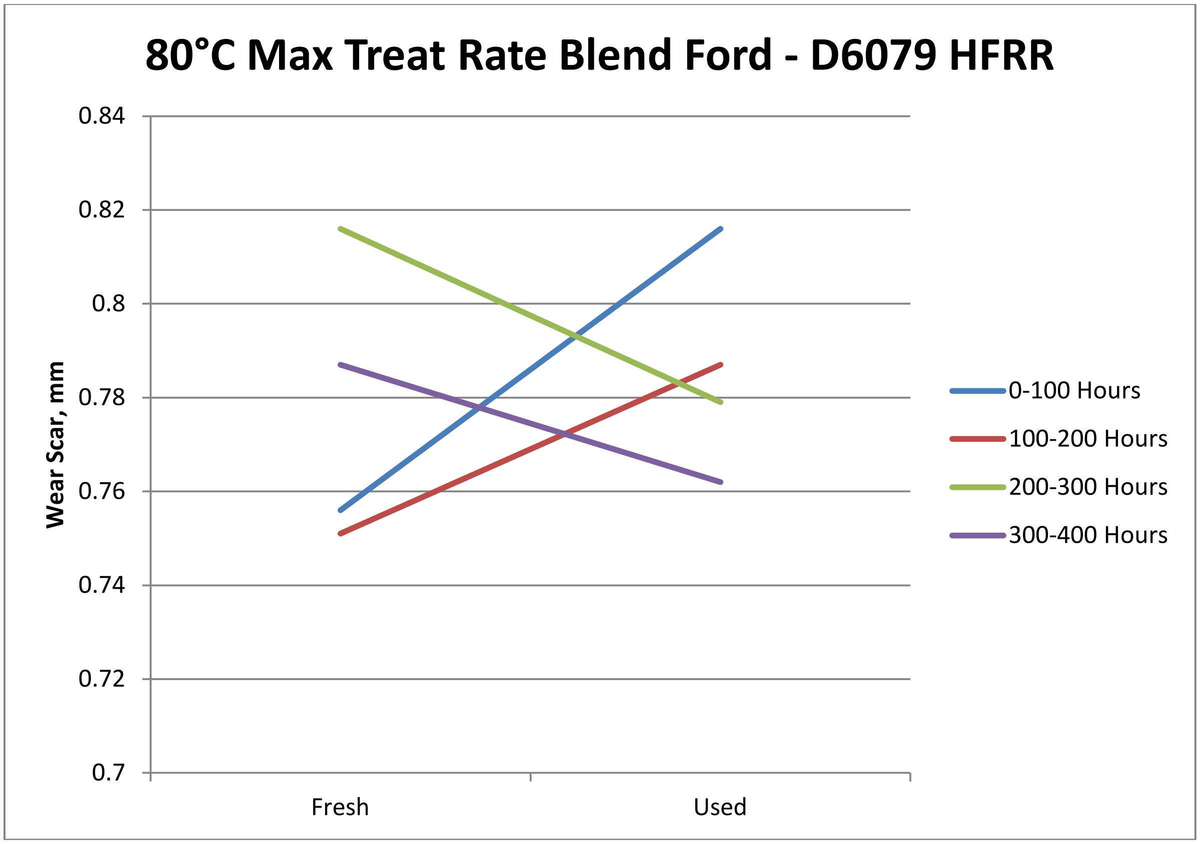

Figure H-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on a Blend of the SPK fuel and Jet A, all treated with 22.5 ppm DCI-4A at 60°C inlet temperature.

Fuel Pump

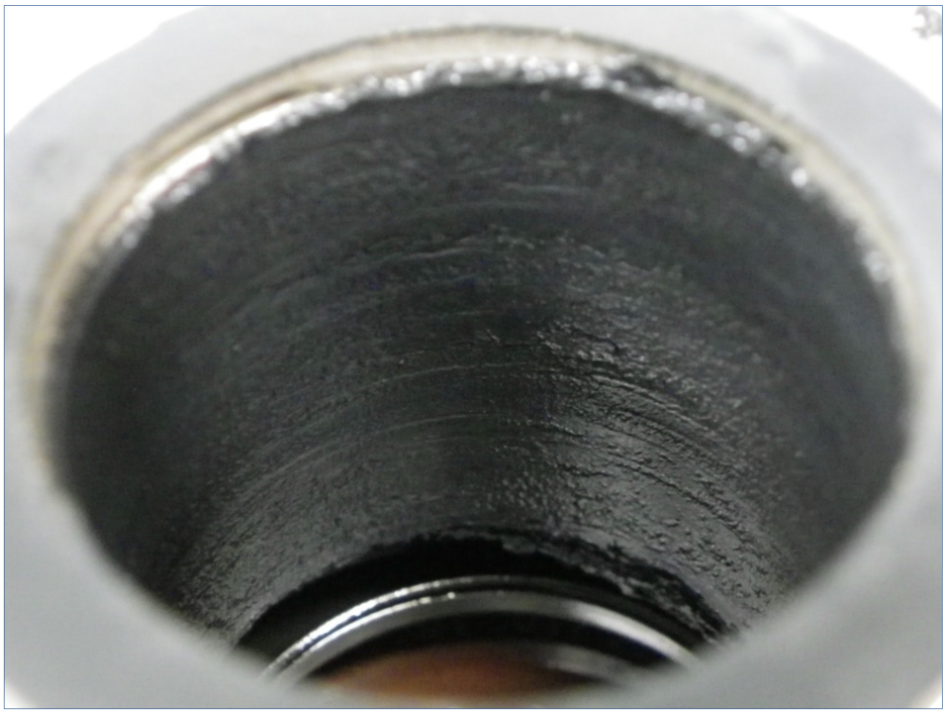

Figure H-9. Front Pump Bushing at 100 Hours

Figure H-10. Front Pump Bushing at 200 Hours

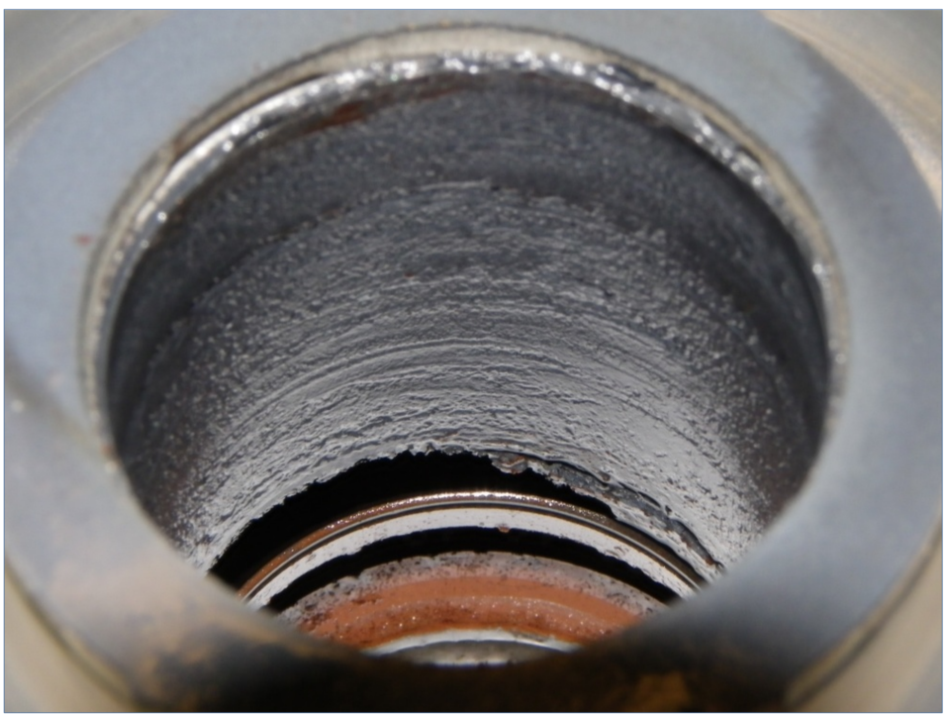

Figure H-11. Front Pump Bushing at 300 Hours

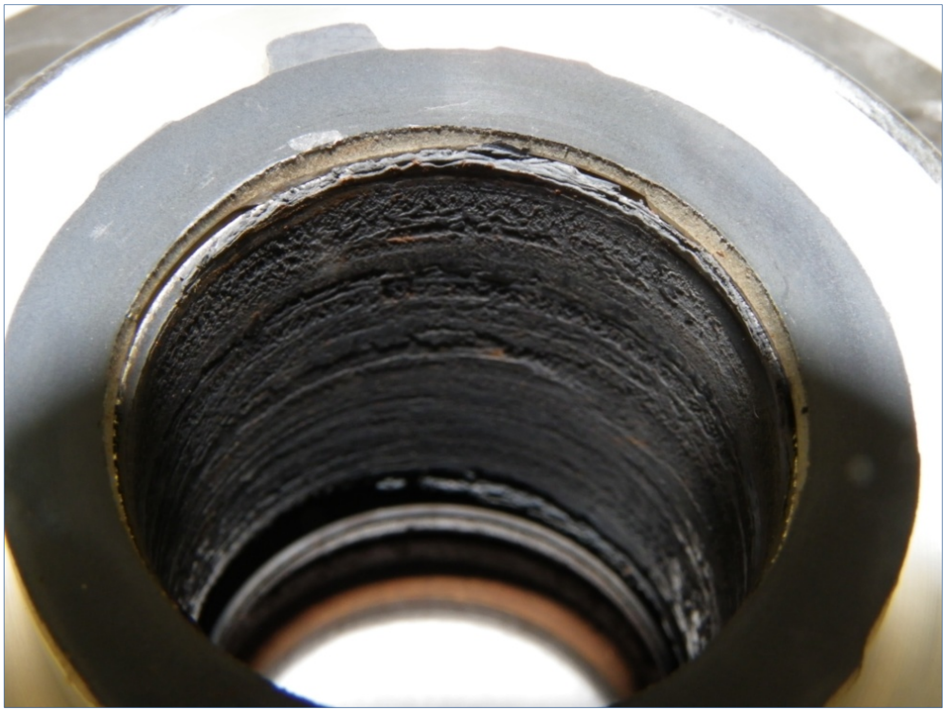

Figure H-12. Front Pump Bushing at 400 Hours

Figure H-13. Rear Pump Bushing

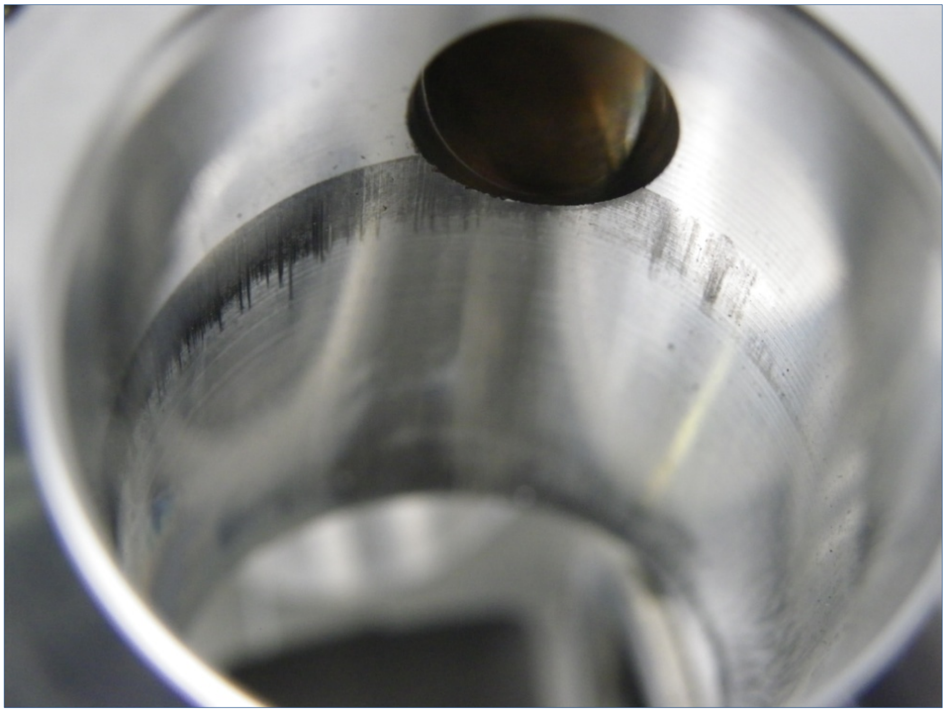

Figure H-14. Left Pump Bore

Figure H-15. Right Pump Bore

Figure H-16. Left Cam Follower Side 1

Figure H-17. Left Cam Follower Side 2

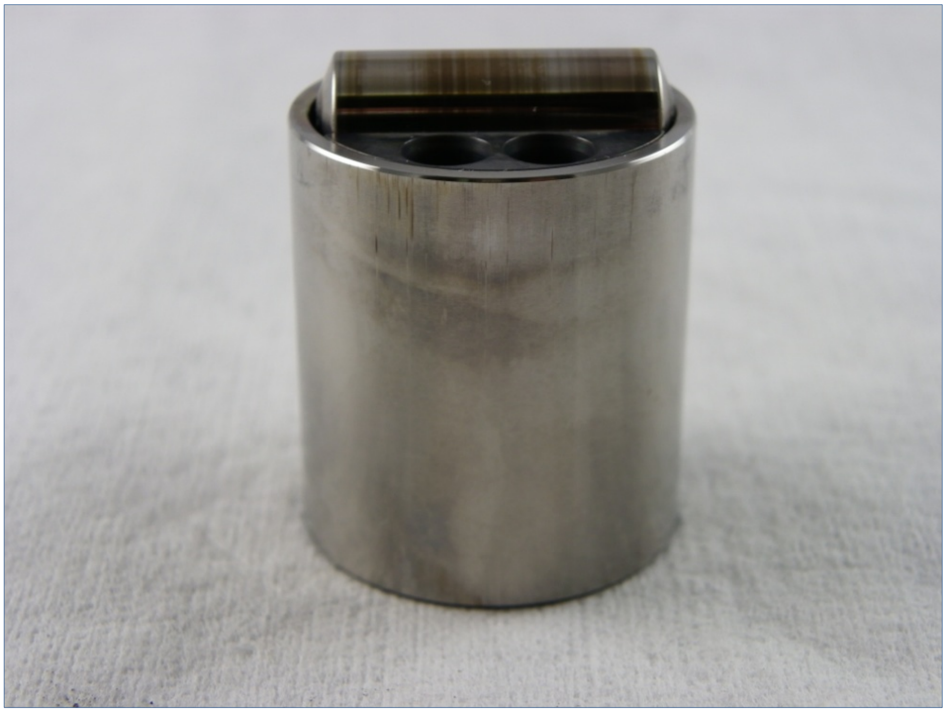

Figure H-18. Right Cam Follower Side 1

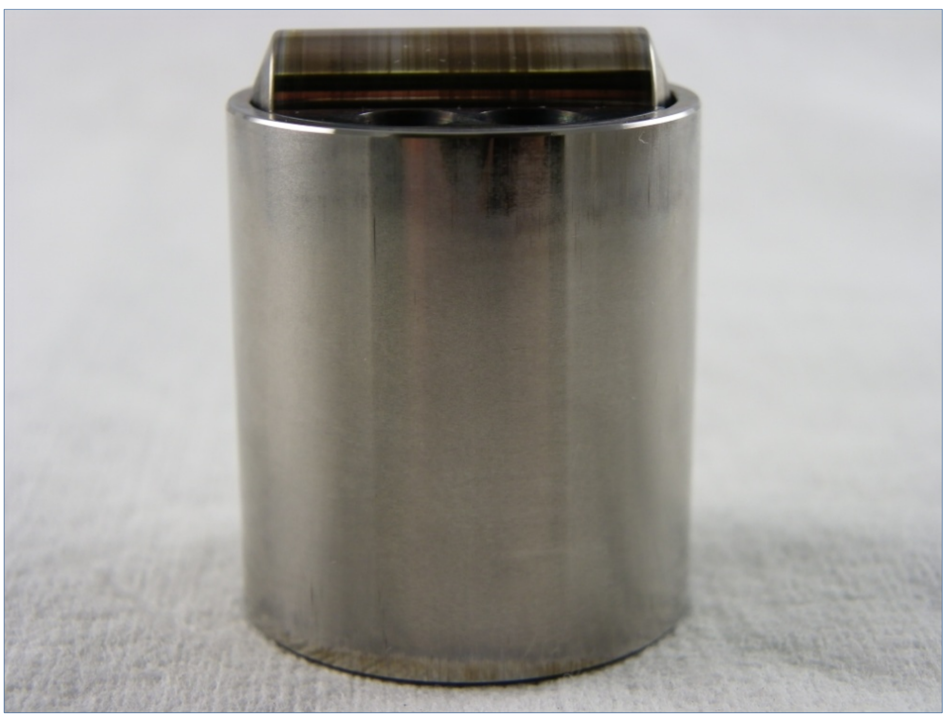

Figure H-19. Right Cam Follower Side 2

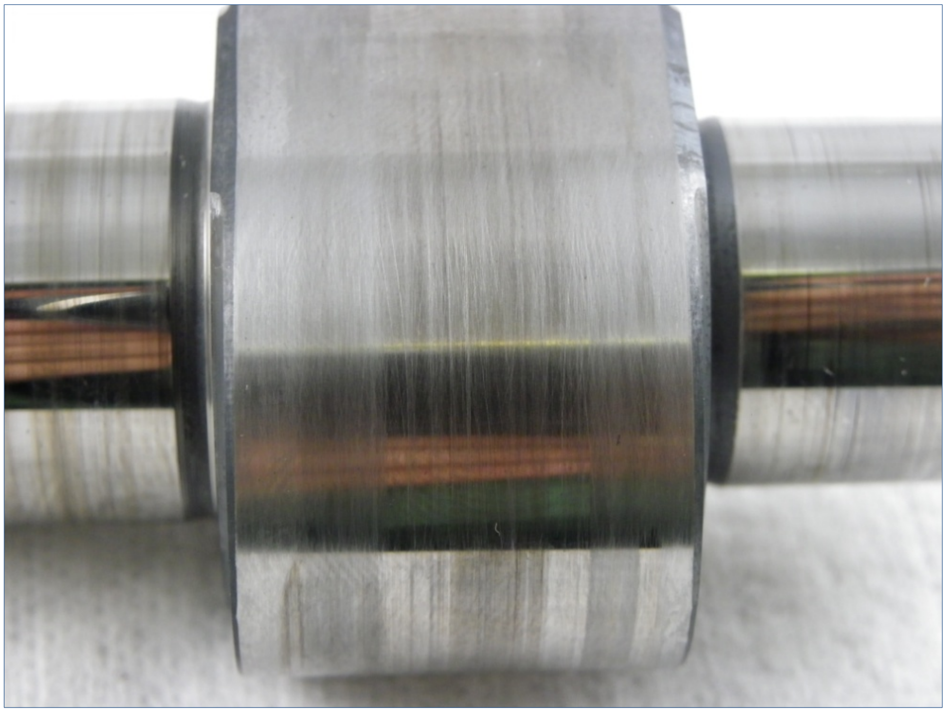

Figure H-20. Camshaft Lobe

Fuel Injector

Figure H-21. Injector Needle

Figure H-22. Upper Hydraulic Coupler Piston Side A

Figure H-23. Upper Hydraulic Coupler Piston Side B

Figure H-24. Lower Hydraulic Coupler Piston Side A

Figure H-25. Lower Hydraulic Coupler Piston Side B

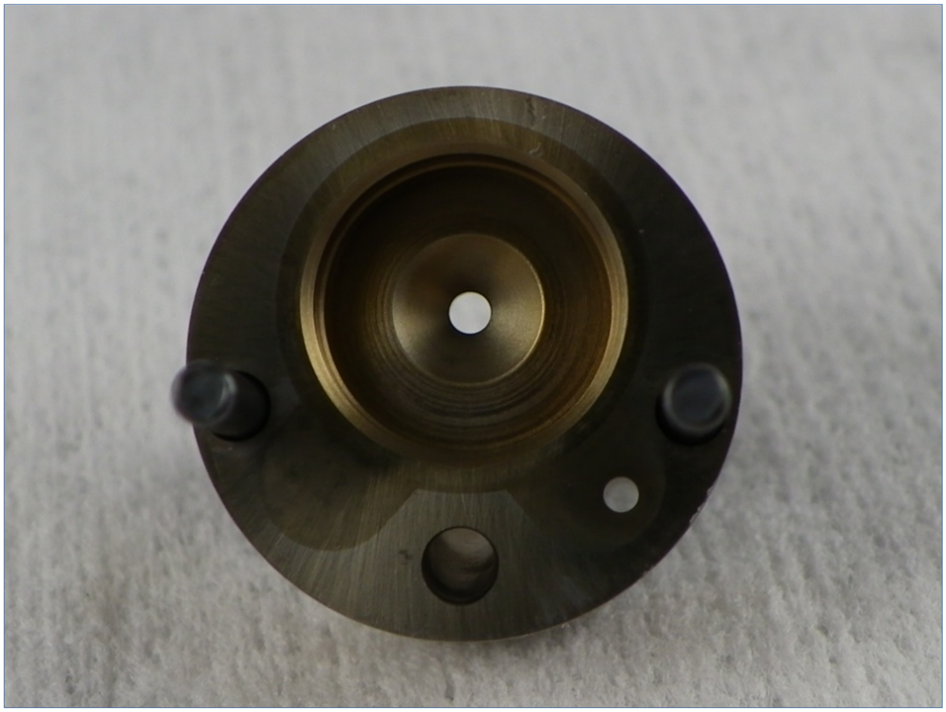

Figure H-26. Intermediate Plate (Top)

Figure H-27. Intermediate Plate (Bottom)

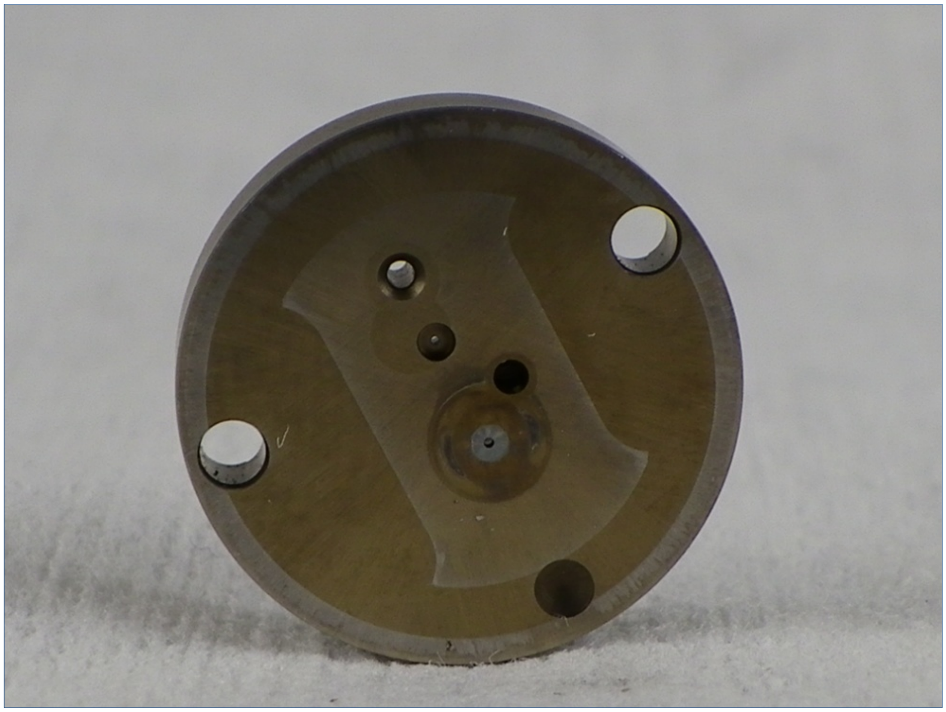

Figure H-28. Control Valve Plate (Top)

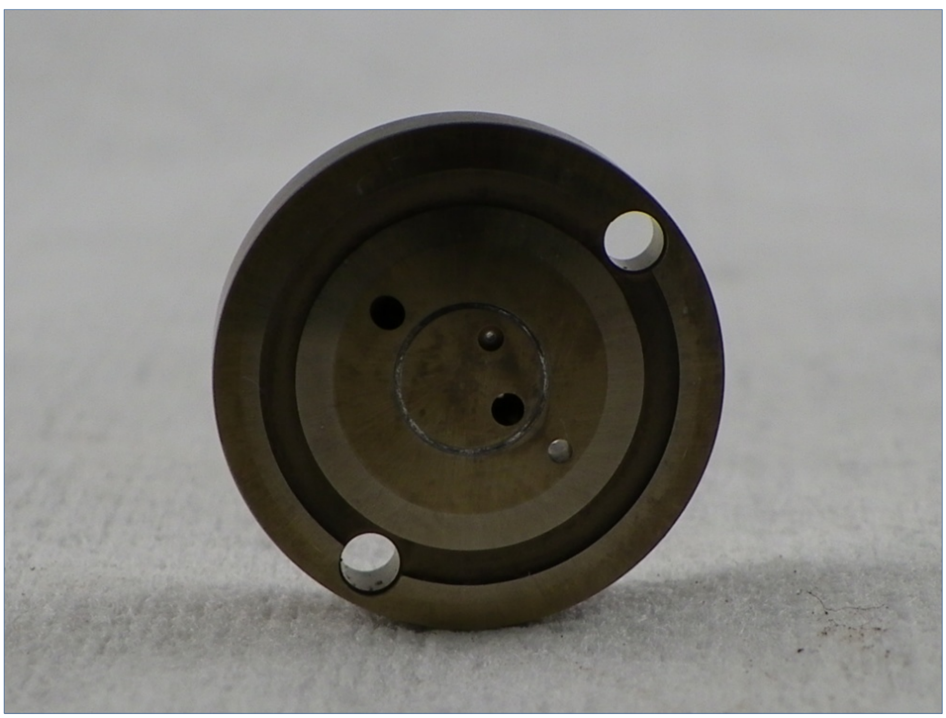

Figure H-29. Control Valve Plate (Bottom)